PETROGRAPHIC CHARACTERISTICS AND PROVENANCE OF FLUVIAL SANDSTONE, SUNNYSIDE OIL-IMPREGNATED SANDSTONE DEPOSIT, CARBON COUNTY, UTAH

by

Elizabeth Young Banks

An abstract of a thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

in

Geology

M. Dane Picard Chairman, Supervisory Committee

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The University of Utah

December 1981

THE UNIVERSITY OF UTAH GRADUATE SCHOOL

SUPERVISORY COMMITTEE APPROVAL

of a thesis submitted by

Elizabeth Young Banks

This thesis has been read by each member of the following supervisory committee and by majority vote has been found to be satisfactory.

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ABSTRACT

The Sunnyside oil-impregnated sandstone deposit (Eocene) is located on the southwestern edge of the Uinta Basin. The sandstone is dominantly arkose. Thin section, microprobe and heavy mineral analyses indicate a mixed provenance of crystalline and sedimentary sources. Primary crystalline detritus was derived from southwestern Colorado and sedimentary detritus from locally adjacent Colorado Plateau uplifts.

The sandstone at Sunnyside was deposited in a meandering fluvial environment. Lacustrine rocks of the Green River Formation overlie and underlie, and are occasionally interbedded with the fluvial rocks. The average paleocurrent direction is N 45° E. The incongruent relationship between the paleocurrent direction and postulated source area is probably due to the presence of the San Rafael Swell upwarp, and the influence upon the drainage pattern by streams that drained the orogenic highlands of western Utah and joined the major northward-flowing drainage at the northern end of the San Rafael Swell.

Migration of bitumen into the rocks at Sunnyside occurred after authigenic development of spar-size dolomite rhombs, syntaxial albite and quartz overgrowths, and hematite. Development of calcite cement may be related to the introduction of bitumen. Correlation of bitumen content with textural data was weak. Incomplete saturation of rocks by bitumen prevent a determination of the effect of mean grain size and percent matrix upon saturation.

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The constant support and understanding of my parents, Dr. and Mrs. Rafe Banks, Jr., and brothers provided me with the desire to complete this project and it is to them that I give my deepest love and appreciation.

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INTRODUCTION

The Sunnyside oil-impregnated sandstone deposit in Carbon County, Utah contains an estimated 3.5 - 4 billion barrels of in-place bitumen (Ritzma, 1973, sheet 2). Measured reserves are estimated at 1.25 billion barrels and indicated reserves at 1.75 billion barrels (Ritzma, 1973). The size of estimated reserves, surface mineable potential of the deposit, and accessibility by road and rail are factors that are presently encouraging serious consideration for commercial development.

Very little geologic information exists with the exception of a few stratigraphic interpretations (Holmes and others, 1948; Murany, 1964, Jacob, 1969, Ryder and others, 1976). No petrographic descriptions or interpretations based upon petrographic studies have been published.

The objectives of this study are to (1) determine the environment of deposition of the oil-impregnated sandstone of the Sunnyside deposit, (2) determine the composition and source of the sediment, (3) determine the average paleocurrent direction of the sandstone and reconstruct the paleogeography that existed during deposition of the Sunnyside deposit, and (4) determine the effect of textural characteristics of the sandstone upon saturation by bitumen.

Definitions

Bitumen is defined by the American Geological Institute (1976, p. 47) as "a general term for various solid and semisolid hydrocarbons which are soluble in carbon bisulfide, whether gases, easily mobile liquids, viscous liquids, or solids". Rocks which contain variable amounts of bitumen in its pore spaces are referred to by the various terms: tar sand or oil sand, bituminous and oil-impregnated. Tar sand and oil sand are terms applied to deposits of bitumen saturated sand in Alberta, Canada. "Bituminous sandstone" has been used by various authors (Holmes and others, 1948; and Wiley, 1967) to describe saturated sandstone deposits in Utah. The term "oil-impregnated", however, is the currently preferred terminology and will be used in this report. "Barren" will be used to refer to rocks within the oil-impregnated sequence which do not contain bitumen.

Procedure

Ninety-two samples of barren and oil-impregnated rocks distributed vertically and laterally throughout the Sunnyside oil-impregnated sandstone deposit were studied. More than 200 points were counted on each thin section for petrologic analysis. Individual grain characteristics were determined by a second point count of 100 grains in 80 thin sections of clastic rocks. Optimal orientation of thin sections for grain textural studies is parallel to bedding (Blatt and others, 1980); however, because detailed mineralogical data was also required, the thin sections were cut perpendicular to bedding. The terminology and grain size divisions of Wentworth (1922) were used for grain size classification. Grain size distributions and statistical parameters, including mean, median and sorting, were determined using Friedman's method (1958) and Folk's equations (1974). Rounding and sphericity were estimated by visual comparison with the roundness chart of Powers (1953). The qualitative character of individual grain contacts were described using the terms summarized in Pettijohn and others (1973, p. 90).

Thirty oil-impregnated samples were disaggregated and sieved into less than 4 mm size fragments. The samples were weighed and refluxed with toluene vapors to extract the bitumen. After refluxion, the samples were dried and reweighed to determine the percent bitumen by weight of the sample. This method of refluxion by Rall and Taliaferro (1946), which is used by the University of Utah Fuels Engineering Dept., is described in Appendix A.

Heavy minerals were separated from four barren samples by the heavy liquid tetrabromethane. The .210 mm to .105 mm size fraction was used. Magnetite was removed from the disaggregated sand before the heavy mineral separation. The heavy mineral separates were mounted in Lakeside 70 for analysis.

Polished grain mounts of five samples of disaggregated sandstone, which was used in the refluxion analysis, were made for microprobe analysis. Percent Or, Ab and An content of feldspars were obtained by a line count (Galehouse, 1971) of 30 feldspar grains per mount. Initially, two analyses per plagioclase grain were taken to determine overgrowth and grain composition. The overgrowth compositions were found to be uniform, so only one count per grain was taken thereafter. The samples were run on a three-channel ARL model EMX-SM electron microprobe. The microprobe was operated at 15 kilovolts excitation voltage, 200 microamp emission current and 30 nanoamp sample current. Raw probe data were collected using a constant integrated beam current-time product. Probe data were corrected for both background and matrix effects using the factors of Albee and Ray (1970). Analyses with totals outside the limits of 95.0 and 101.5 percent feldspar molecule were eliminated. The remaining analyses were recalculated so that An + Or + Ab totaled 100 percent.

One sandstone was analyzed for clay composition by X-ray diffraction. Four prepared samples: 1) air dried, 2) 250° for 1 hour, 3) 550° for 1 hour, 4) glycolated at 60° C were analyzed. All samples were run at 40 kV and 20 MA with Cu k-alpha X-radiation.

Location

The area of study is located on the southwestern flank of the Uinta Basin in Carbon County, Utah (see Fig. 1). The Sunnyside oil-impregnated sandstone deposit outcrops between 9,000 to 10,000 feet (2740 to 3050 m) near the crest of the Roan Cliffs, a northwest-southeast trending escarpment subparallel to the Book Cliffs.

Previous Work

Holmes and others (1948) were the first to study in detail the Sunnyside deposit. They mapped the outcrops of oil-impregnated sandstone of the deposit on the western face of the Roan Cliffs on a scale of 1:24,000. A smaller area, the zone of the thickest sequence of oil-impregnated sandstone, was mapped on a scale of approximately

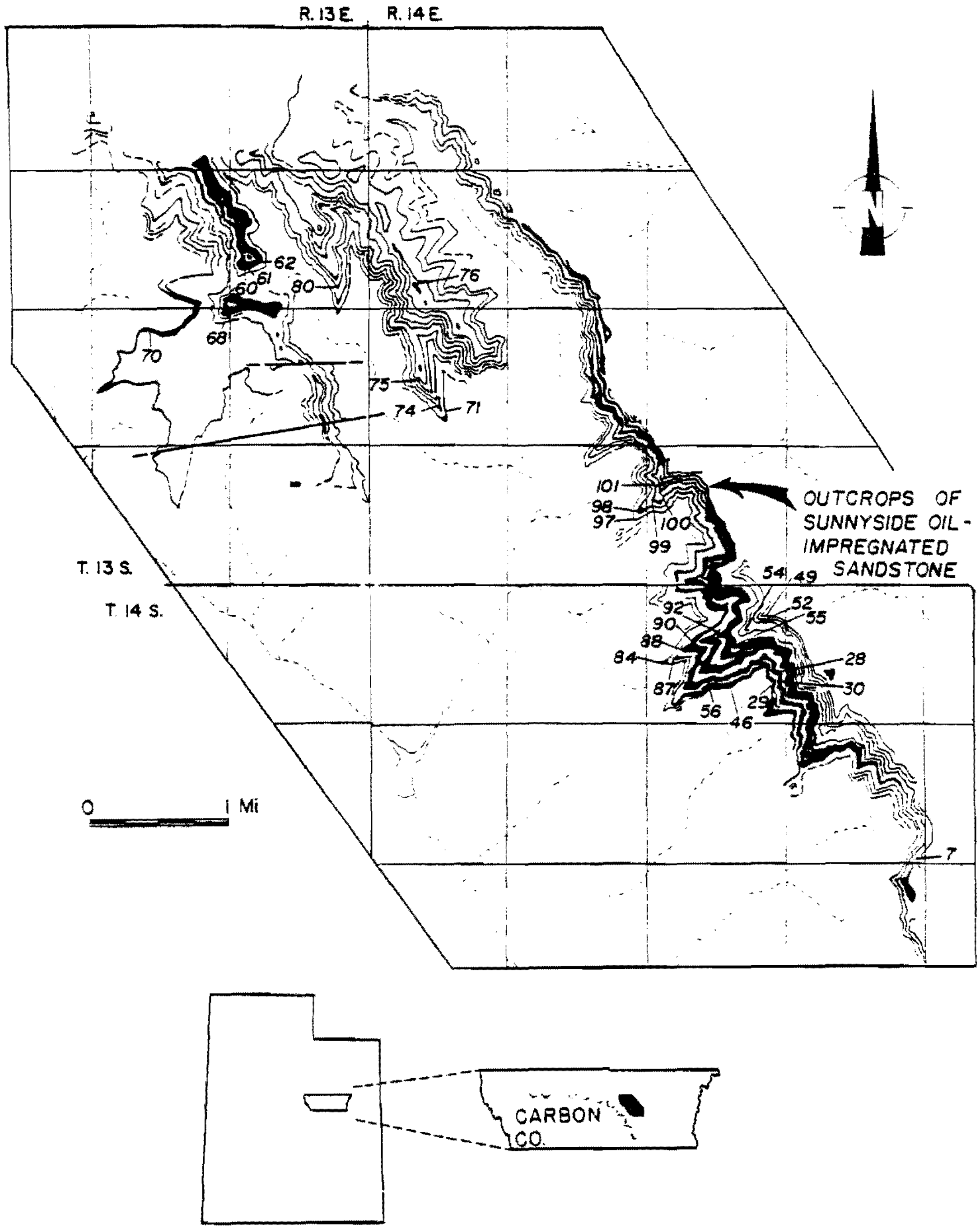


FIG. 1.--Location and outcrop map of the Sunnyside oil-impregnated sandstone deposit. Outcrops of oil-impregnated sandstone beds modified from Holmes and others (1948) to fit U. S. Geological Survey 7-1/2' topographic quadrangles. Number and leaders indicate sample numbers (SS) and location of samples analyzed for percent bitumen by weight.

1:5,000. A stratigraphic section was measured through this interval. More than twenty years later, Jacob (1969) measured another stratigraphic section in the Sunnyside area, as part of a study of the delta facies of the Green River Formation. These are the only two works which present detailed stratigraphic descriptions. Other workers (Murany, 1964; and Ryder and others, 1976) have used these descriptions, along with their own work, to place stratigraphically the Sunnyside deposit within the Eocene stratigraphic framework of the Uinta Basin. No detailed petrologic information has been published.

Paleogeographic Setting

During the Cretaceous period, the Rocky Mountain geosyncline occupied the Western Interior. Clastic sediments were shed eastward into the geosyncline trough from the Sevier orogenic belt in western Utah and Nevada (Armstrong, 1968). In the latest Cretaceous time, compressive forces resulted in thrusting near the western edge of the Uinta Basin area.

At the close of the Cretaceous period the seas withdrew as epeirogenic uplift raised the Colorado plateau region above sea level to an elevation of approximately 1,000 feet (Bradley, 1929b, p. 90). Tertiary orogenic development of the Rocky Mountains began in the Western Interior and intermountain basins developed on the Colorado Plateau. As the Rocky Mountains developed and began to rival the Sevier orogenic belt in size, the continental divide became unstable. An eastward shift of the divide to the Rocky Mountain region led to ponding of drainages. During Paleocene time Flagstaff Lake formed in central Utah extending southward possibly as far as northern

Arizona. The depositional center of lacustrine sedimentation shifted northeastward from east-central Utah to northeastern Utah during the Eocene epoch. Great thicknesses of sediment accumulated in the Uinta Basin as streams and rivers flowing across low-lying piedmont plains carried sediment into Eocene Lake Uinta. Recession of the lake began during middle to late Eocene.

The configuration of the Uinta Basin is a result of Laramide tectonics (Osmond, 1964). The rise of the Uinta Mountains to the north of the basin during the Tertiary was probably the most influential factor in the development of the asymmetrical configuration of the basin. The east-west trending synclinal axis of the basin lies near the northern rim, a steeply-dipping and locally overthrust flank. The gently-dipping southern rim of the basin was influenced by the development of the Tertiary positive features, the San Rafael Swell and the Douglas Creek Arch.

STRATIGRAPHY

Thickness

The oil-impregnated section at Sunnyside is more than a thousand fee thick. As a result of erosion, the upper part of the section gradually thins to a thickness of 300 feet on the south. Holmes and others (1948) noted exposures of oil-impregnated rocks east of the main outcrop trend in the canyons of Dry Creek, Range Creek, and Cottonwood Canyon, but they did not include them in their study. Campbell and Ritzma (1979) note the occurrence of oil-impregnated rocks in canyons eight miles east of the main outcrop. They estimate a 75% reduction in the thickness of the oil-impregnated section in as little as 1.5 miles east of the main outcrop based on drill core information.

Age

The Wasatch Formation is lower Eocene in age based on the vertebrate fauna (Bradley, 1931, p. 7). A middle Eocene flora is characteristic of the overlying Green River Formation (Bradley, 1931, p. 9). The oil-impregnated section at Sunnyside is transitional between the Wasatch and Green River formations as shown by the intertonguing of the two formations in the study area. Thick oil-impregnated fluvial channel sandstone within the section at Sunnyside are typical of the Wasatch Formation and are correlated with the

Wasatch Tongue (Ryder and others, 1976). However, Green River facies underlie and overlie the fluvial sandstone. The age assignment of the oil-impregnated interval is therefore middle Eocene.

Fossils

A variety of fossils are present at the Sunnyside locality (Holmes and others, 1948). They are: gar pike or *Lepisisteus cuneatus* Cope, *Knightia atta* (Leidy); crocodile or *Mioplosus* c. f. *abbreviatus* Cope; Turtle(?); freshwater gastropods, "*Planorbis*" *spectabilis* Meek, *Physa* aff. P. *bridgerenis* Meek; and freshwater ostracodes, algae, and plant fragments. A lower Eocene age was suggested by Holmes and others (1948) for the invertebrates but they note that the upward range of these fossils in the Eocene are not well known. A younger age is possible.

Correlation

Stratigraphic correlation of the oil-impregnated section at Sunnyside within the framework of Eocene rocks in the Uinta Basin has changed throughout the years. Figure 2 illustrates correlations made by various workers. The correlations on Figure 2 are accompanied by a stratigraphic section (revised from Holmes and others, 1948) to illustrate lithologic variation within the section and the divisions based upon these variations.

The lower two-thirds of the measured section is correlated with the Wasatch Formation and the upper one-third with the basal Green River Formation (Holmes and others, 1948). Murany (1964) correlated

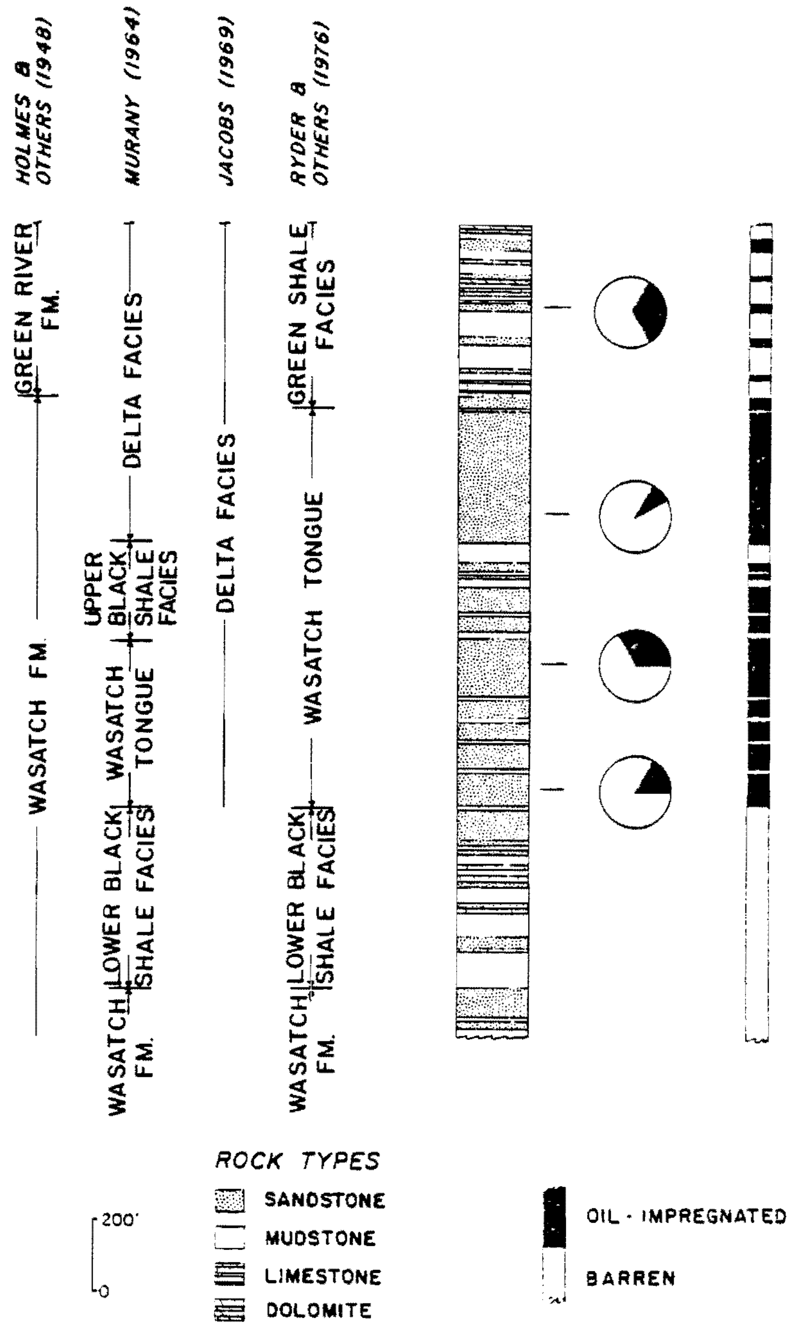


FIG. 2.--Evolution of the stratigraphic nomenclature for the Sunnyside oil-impregnated sandstone deposit. A measured stratigraphic section through the deposit (revised from Holmes and others, 1948) accompanies the stratigraphic divisions. Compass diagrams illustrate significant modes of paleocurrent measurements at that horizon.

the base of the measured section with the Wasatch Formation. The rocks above the Wasatch Formation are correlated as follows:

1) 500 feet of barren carbonate and siltstone equivalent to the lower black shale facies of the Green River Formation, described by Picard (1955 and 1959);

2) 450 feet of oil-impregnated sandstone equivalent to the Wasatch Tongue (Bradley, 1931);

3) 275 feet of oil-impregnated sandstone and barren siltstone equivalent to the upper black shale facies;

4) the remainder of the section equivalent to the delta facies of the Green River Formation, originally described by Bradley (1931).

Jacob (1969) considers the section younger than Holmes and others (1948) and Murany (1964). He correlates the entire oil-impregnated section with the delta facies of the Green River Formation, based on the presence of a 3 foot oil shale which he identifies as the Mahogany oil shale bed (Bradley, 1931, p. 23).

Ryder and others (1976) have examined the Tertiary strata in western Uinta Basin. Their stratigraphic placement of the oil-impregnated sandstones at Sunnyside has been interpreted from a cross-section of southwestern Uinta Basin through the Sunnyside area, using the terminology of Picard (1955, 1957, and 1959) for the Green River Formation. The Wasatch Formation and the black shale facies are equivalent to those of Murany (1964). The carbonate marker unit (Ryder and others, 1976, p. 497) is identified as within the black shale facies. Above the black shale facies, the stratigraphic interpretation of Ryder and others (1976) differs from that of Murany (1964). Ryder and others (1976) consider the entire thick section of oil-impregnated sandstone, approximately 1,100 feet thick, as equivalent to the Wasatch Tongue. The green shale facies (Picard, 1957), which contains lacustrine siltstone, shale and ostracodal and algal carbonates overlies the Wasatch Tongue. The middle marker unit which is used for subsurface correlation in the Uinta Basin (Ryder and others, 1976) is approximately 80 feet from the top of the section.

The Mahogany oil shale identified by Jacob (1969) below the top of the section is the middle marker unit of Ryder and others (1976). The Mahogany oil shale is stratigraphically above the section at Sunnyside and therefore not present due to erosion of the remainder of the overlying Green River Formation.

PETROGRAPHY

Texture

Roundness of the grains varies with grain size. Figure 3 illustrates the increase of grain angularity with a concomitant decrease in mean grain size. In medium-grained sandstone the largest percentage of grains is subangular, whereas the finer grain size groups are dominated by angular grains with very fine-grained sandstone and coarse siltstone exhibiting the greatest degree of grain angularity. All three groups have a very low percentage of well-rounded grains (Fig. 3). Picard (1966, p. 907) notes a similar trend in siltstones in which the angularity of silt-size grains increases as sorting and average grain size decreases. The development of authigenic overgrowths on Na-plagioclase and quartz have increased the angularity of grains that were once subrounded to subangular.

The sphericity of 100 grains in each thin section of clastic rocks was estimated using Powers (1953) visual comparison chart. An average of 19.7% of the grains has a highly spherical shape and 80.3% exhibit low sphericity. No relationship between sphericity and grain size was found.

The degree of sorting of the terrigenous rocks, both barren and oil-impregnated, increases with an increase in grain size and varies from poorly- to well-sorted. Table 1 illustrates the relationship between grain size and sorting. Measurements of sorting in the 1-2 phi grain size class of barren sandstones were insufficient to obtain

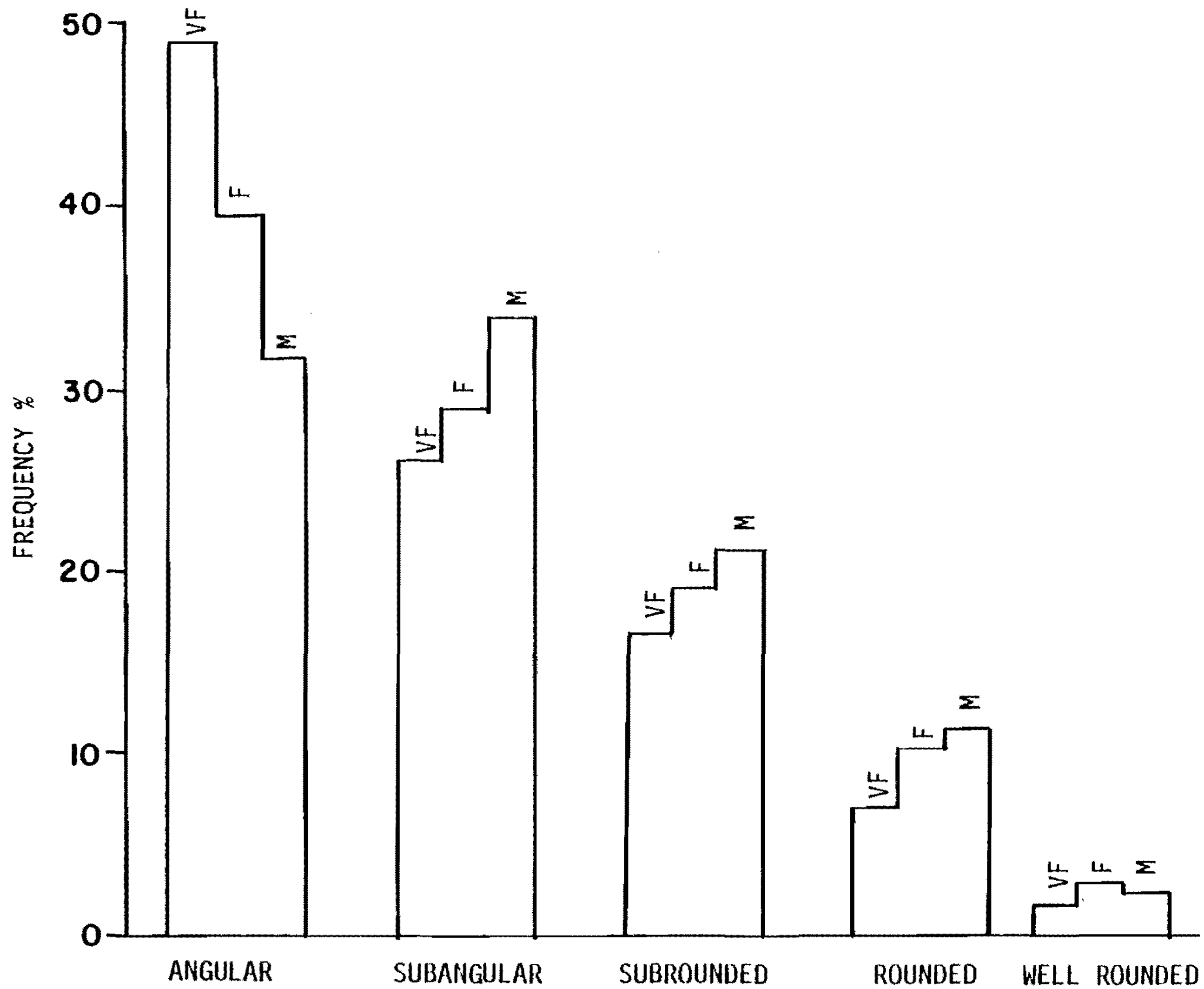


FIG. 3.--Distribution of grain angularity classes (after Powers, 1953). VF - very fine-grained sandstone and coarse siltstone; F - fine-grained sandstone; M - medium-grained sandstone.

TABLE 1. - Average Degree of Sorting in Three Grain Size Groups of Barren and Oil-Impregnated Rocks in the Sunnyside Oil-Impregnated Sandstone Deposit.

	BARREN	OIL-IMPREGNATED	TOTAL
1-2 phi	------	.5015	.5015
2-3 phi	.5043	.5432	.5320
3-5 phi	.8736	.6951	.7612

an average. Distribution of sorting in the barren and oil-impreganted clastic rocks is illustrated in Figures 4 and 5 respectively. There is no discernable difference between the degree of sorting in the two groups. More than 50% of the barren and oil-impregnated rocks are moderately well-sorted and more than 30% are well-sorted.

Mean grain sizes of the terrigenous rocks varies from medium-grained sandstone to coarse siltstone. Both barren and oil-impregnated clastic rocks have a unimodal distribution and positive skewness (Figs. 6 and 7). Fine-grained sandstone constitutes the greatest size fraction.

Regression analysis was used to obtain a statistical measure of the relationship between sorting and mean diameter in the samples of barren and oil-impregnated rocks. A distinct correlation exists, as shown in Figures 8 and 9. Variability of sorting increases as grain size decreases.

Moderate compaction of the sand grains has lead to an increase in grain contacts. Long contacts (Taylor, 1950, p. 707) are among the most common averaging 64%. Point contacts average 31.6% and floating grains average 3.9%. Sutured and concavo-convex contacts were not observed. There is no distinction between barren and oil-impregnated rocks in the frequency of occurrence of the three types of contacts. Grains are commonly aligned with long axes parallel to bedding. Compaction of the sandstone and siltstone has lead to deformation of ductile grains and breakage of brittle grains.

The four textural maturity classes of Folk's textural maturity index (1974) -- immature, submature, mature, and supermature -- are

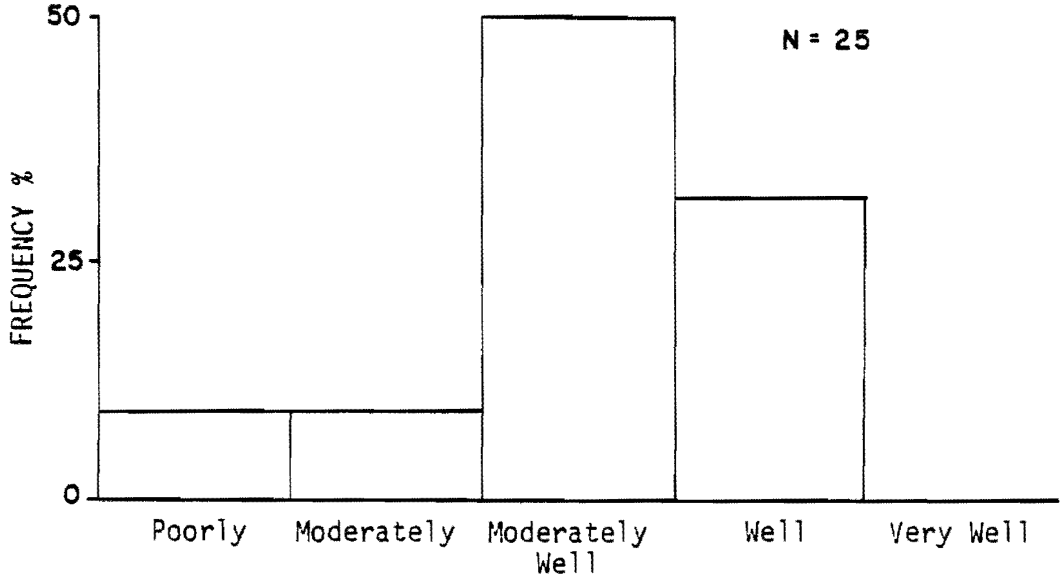


FIG. 4.--Degree of sorting of Sunnyside barren clastic rocks.

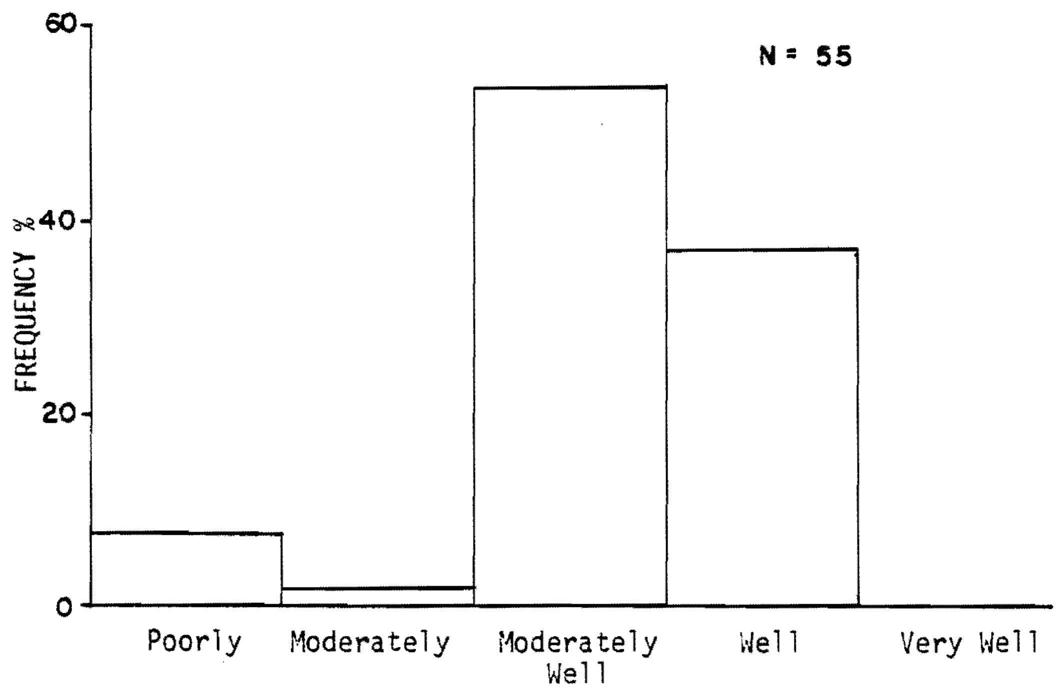


FIG. 5.--Degree of sorting of Sunnyside oil-impregnated clastic rocks.

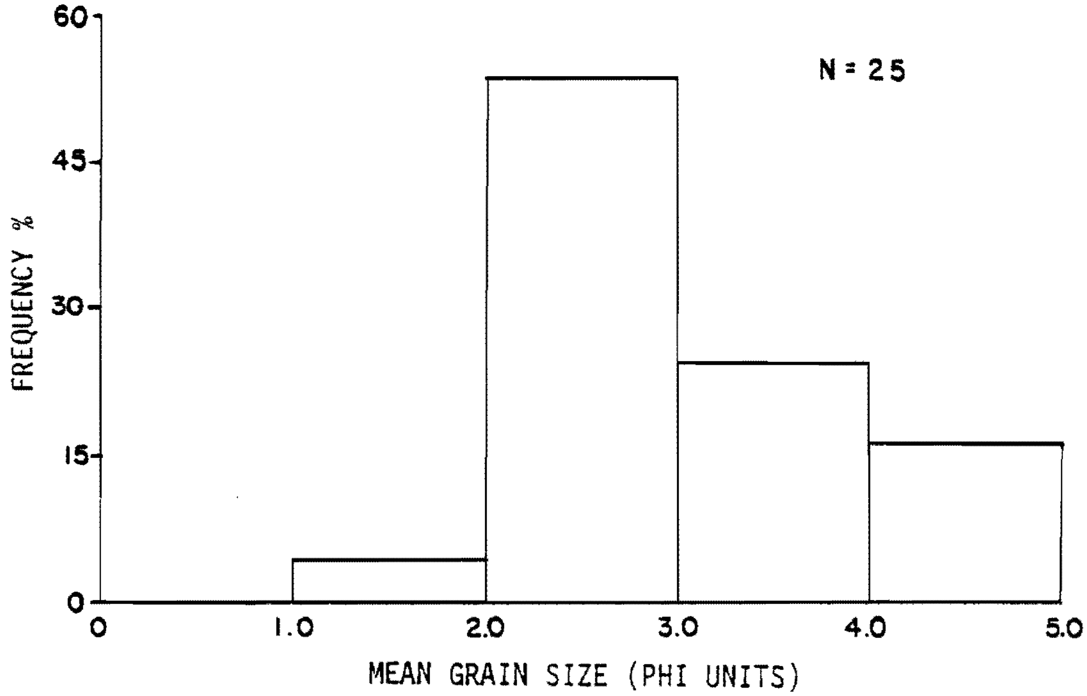


FIG. 6.--Mean grain size distribution of Sunnyside barren clastic rocks.

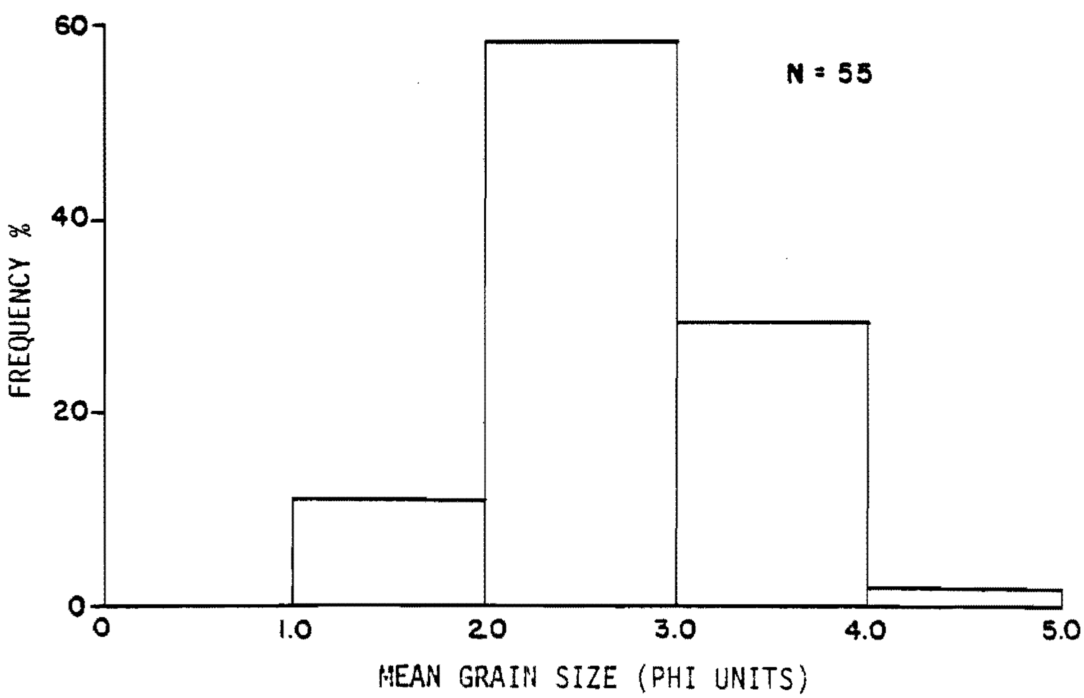


FIG. 7.--Mean grain size distribution of Sunnyside oil-impregnated clastic rocks.

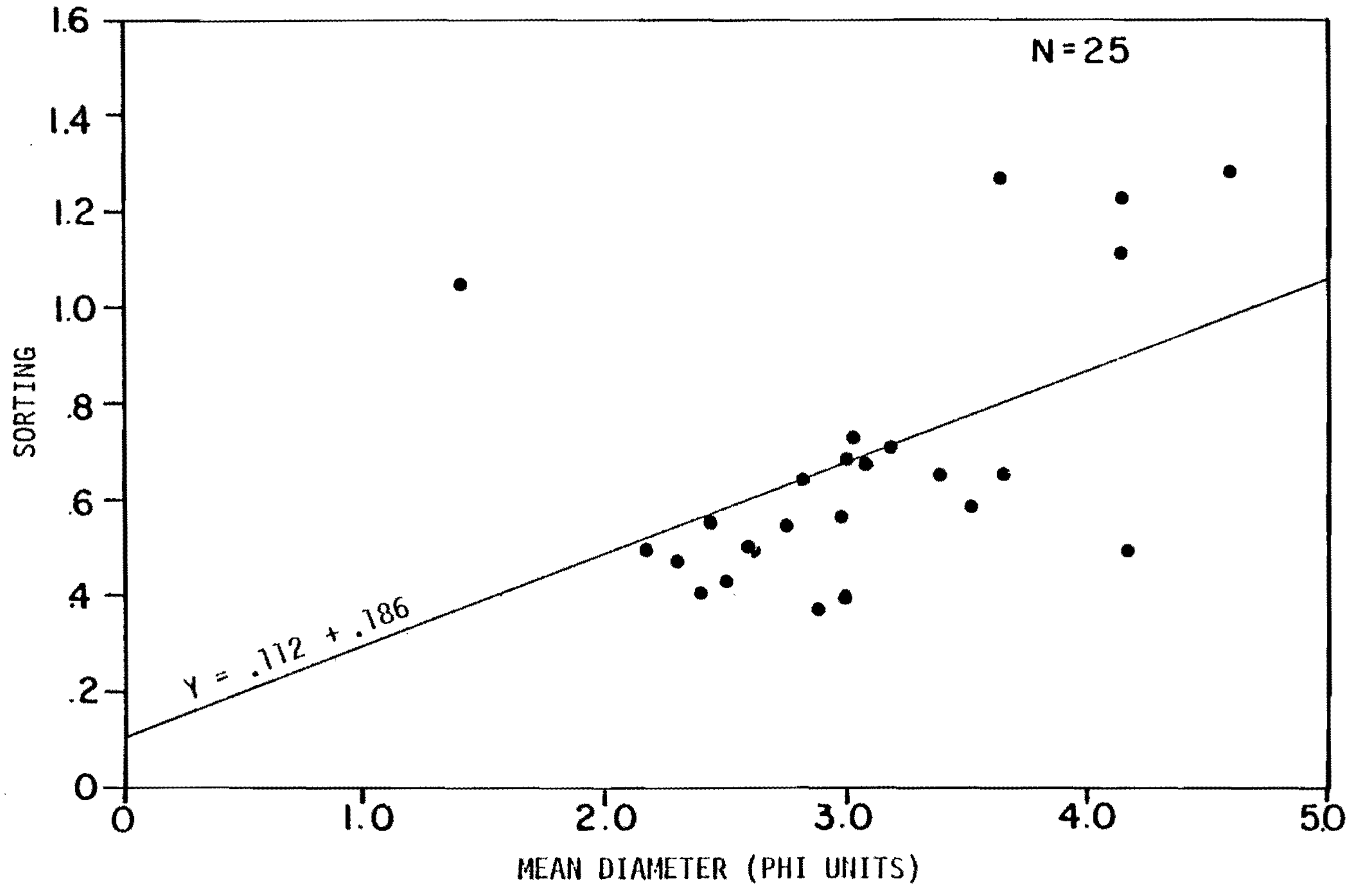
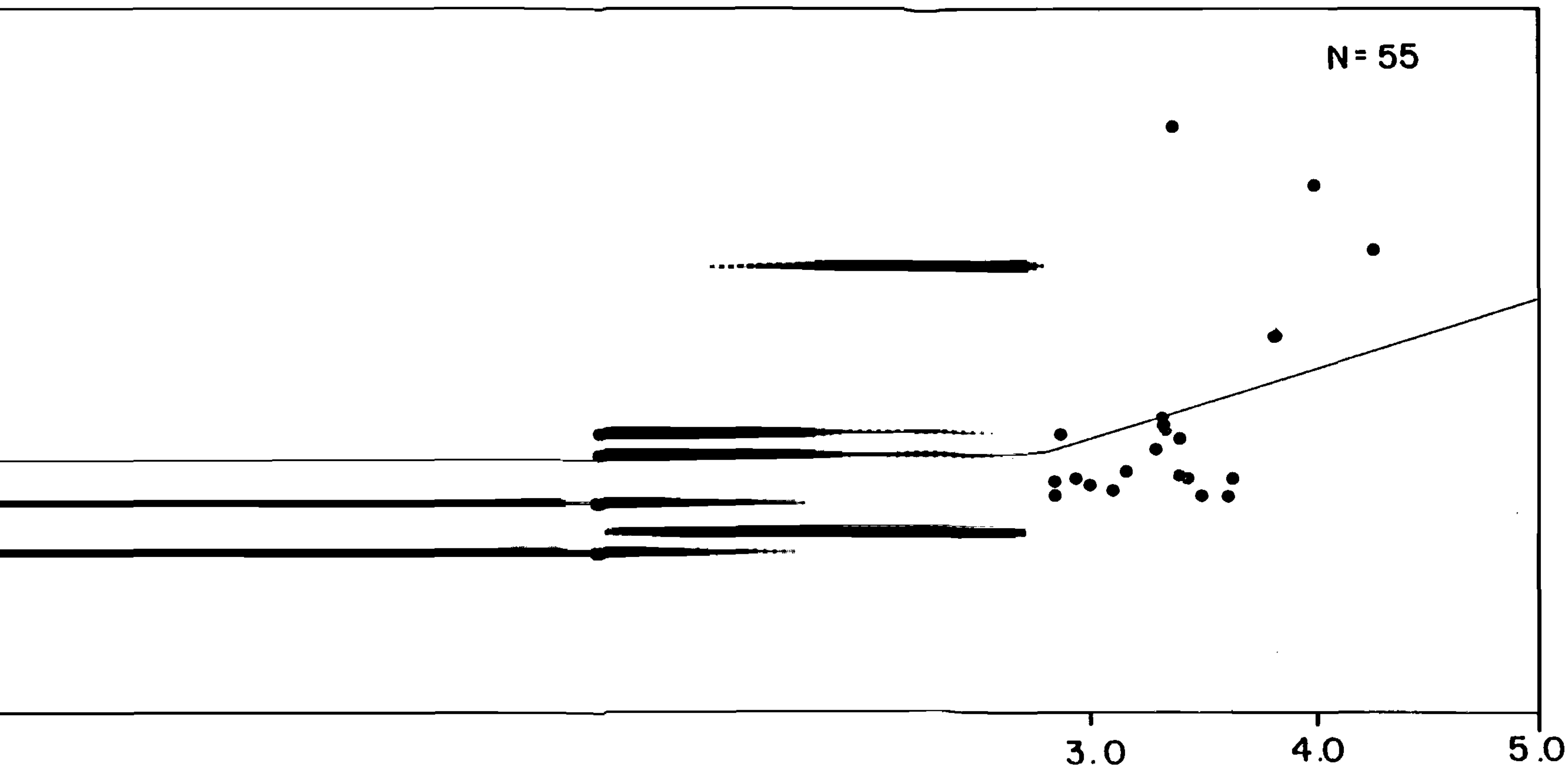


FIG. 8.--Scatter diagram of mean diameter versus sorting of Sunnyside barren clastic rocks. Correlation coefficient = .492.



UNITS)

f Sunnyside oil-impregnated clastic

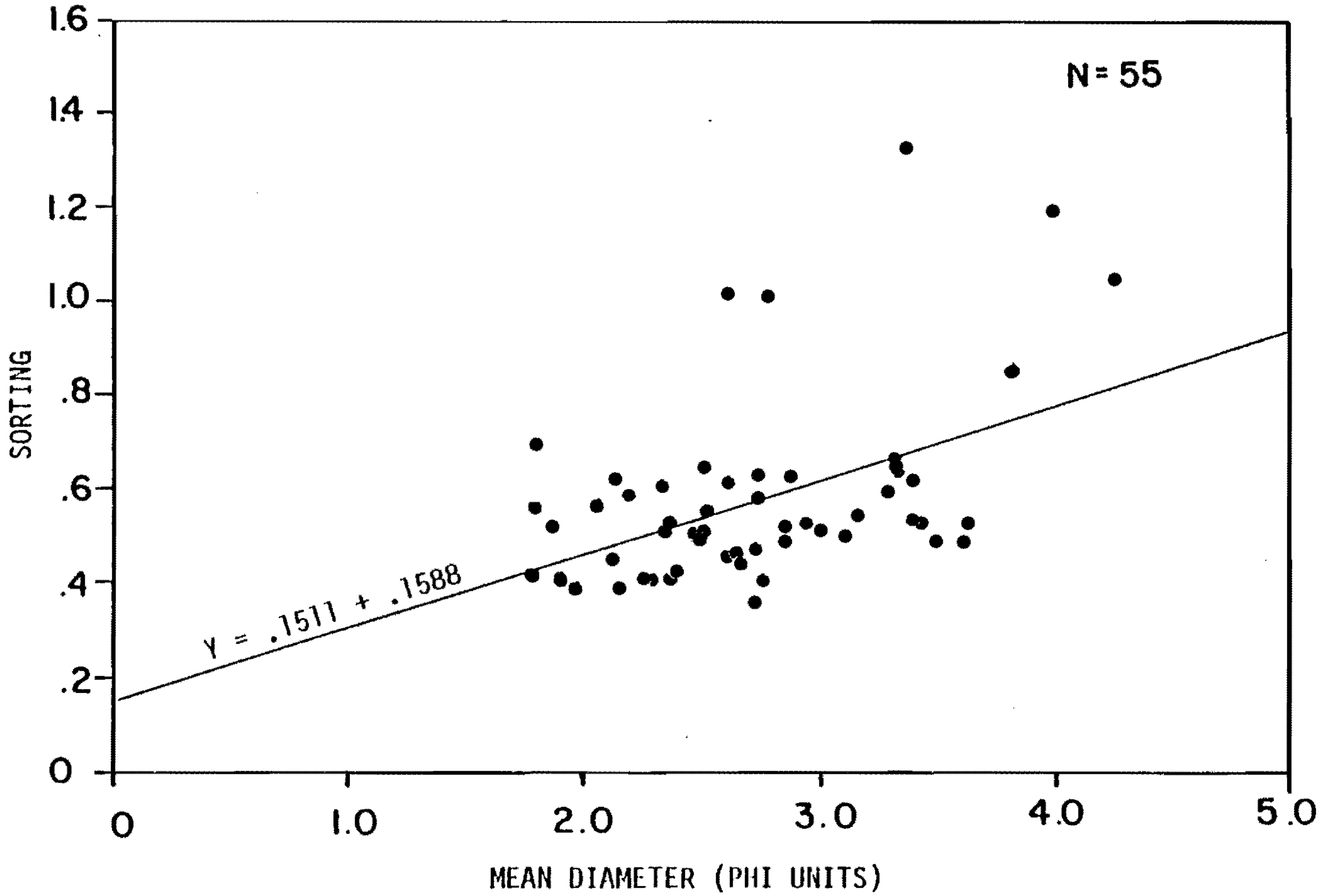


FIG. 9.--Scatter diagram of mean diameter versus sorting of Sunnyside oil-impregnated clastic rocks. Correlation coefficient = .477.

divided on the basis of three major textural parameters: clay content, sorting and roundness. Textural maturity of sandstone is generally considered a direct result of the depositional environment. When the depositional environment of a sandstone is viewed in the complete paleoenvironmental framework of an area, textural maturity can also be an indicator of tectonic activity or stability (Folk, 1974, p. 108). The fluvial sandstone of the Sunnyside area is predominately classed as submature and, rarely, mature. According to Folk (1974, p. 106), fluvial channel sandstone commonly is submature to mature.

Composition

Thin sections of ninety-two barren and oil-impregnated rocks were studied using petrographic and binocular microscopes. To aid in the identification of carbonates and feldspars the thin sections were stained for calcite and potassic feldspar (Friedman, 1971).

Modal analyses of the 92 samples are given in Tables 2, 3, and 4. Terrigenous rocks are those which have over 50% clastic fraction (Folk, 1974). The modal analyses of the terrigenous samples are subdivided into barren and oil-impregnated groups. Rocks composed of more than 50% chemical constituents, both allochemical and orthochemical, are grouped as chemical rocks (Folk, 1974).

The sandstone classification scheme of Folk (1968) is used for the compositional analysis of the terrigenous rocks (Fig. 10). The average medium-grained sandstone is a lithic arkose. The fine-grained sandstone and the very fine-grained sandstone and coarse siltstone are almost totally arkosic in composition. The

Abbreviations in Tables 2, 3 & 4

monocrystalline quartz	mq
polycrystalline quartz	pq
plagioclase	plg
orthoclase	o
microcline	mi
rock fragments	rf
calcite cement	cal cem
dolomite cement	dol cem
hematite	hem cem
clay	cly
heavy minerals	hvy
mica	mc
pore space	ps
matrix	mat
bitumen	bit
allochems	all
ostracodes	ost
oolites	ool
intraclasts	int

Table 2. Modal Analyses, Oil-Impregnated Clastic Rocks (%)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SS-1	35.0	3.1	19.0	12.9	4.3	15.9	0.0	0.6	0.6	0.0	0.0	0.6	8.0	0.0	0.0	0.0
2	25.8	2.9	12.9	11.9	2.4	8.1	0.0	3.3	0.5	0.0	7.6	0.0	22.9	0.0	1.9	0.0
3	30.5	4.0	14.0	12.0	1.0	5.0	0.0	10.0	0.0	0.0	1.5	1.0	0.5	3.0	17.5	0.0
7	33.3	2.7	15.1	8.0	4.4	11.5	0.0	0.0	0.0	0.0	0.0	0.0	14.7	0.0	10.2	0.0
10	22.2	1.8	10.4	8.0	0.5	17.4	34.4	2.4	0.0	0.0	0.0	0.5	0.0	0.0	2.4	0.0
12	25.0	2.5	18.0	12.0	4.5	9.5	0.0	0.5	3.5	0.0	0.0	1.5	12.0	1.0	10.0	0.0
14	28.0	2.5	18.5	14.5	2.0	10.5	0.0	3.5	1.5	0.0	1.0	0.0	0.0	0.0	15.0	0.5
15	18.2	2.0	5.9	8.4	1.0	2.5	37.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.8	9.8
16	26.3	2.0	12.9	14.4	2.5	4.0	8.9	4.0	0.0	0.0	1.0	0.5	0.0	0.0	24.7	0.0
19	25.9	0.5	12.7	13.2	1.0	3.0	0.0	5.9	3.4	0.0	0.0	0.5	0.0	0.0	34.1	0.0
20	30.2	1.4	10.9	7.5	1.9	7.1	0.0	18.9	0.0	0.0	0.0	0.5	0.0	0.0	17.5	3.3
24	35.4	0.9	24.5	9.4	1.4	6.1	0.0	3.3	3.3	0.0	0.0	0.5	0.0	0.0	14.6	0.5
25	31.1	1.8	14.5	6.8	0.9	6.8	0.0	2.7	2.7	0.0	2.3	0.5	5.4	0.0	10.4	0.0
28	30.9	2.9	21.9	14.3	1.9	9.5	0.0	4.3	0.0	0.0	0.0	1.0	1.9	0.0	8.8	0.0
29	34.4	1.4	15.4	11.3	1.8	5.1	0.0	6.3	1.4	3.2	0.5	0.5	10.8	0.0	5.9	0.5

Table 2. (cont.)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SS-30	31.0	2.0	22.0	10.0	3.0	9.0	0.0	1.5	0.5	0.0	0.0	2.0	2.5	0.0	5.0	0.0
37	32.2	1.0	11.5	9.5	2.5	6.0	0.0	2.0	6.5	9.5	0.5	0.5	3.5	0.0	7.5	0.0
38	31.1	1.5	17.0	6.8	4.9	6.7	2.5	7.3	1.5	0.0	0.5	0.0	4.9	0.0	15.0	0.0
40	38.2	0.0	15.4	7.4	2.8	4.3	0.0	4.2	2.3	0.0	0.5	0.5	4.2	0.0	12.6	7.0
41	29.9	2.3	15.1	8.5	1.9	10.4	0.0	0.9	5.9	0.0	0.0	0.5	1.9	1.4	21.3	0.0
44	23.3	3.1	15.0	7.8	2.6	4.3	0.0	0.0	16.4	1.7	0.9	0.4	3.0	0.0	21.6	0.0
46	32.6	3.3	19.8	5.5	1.5	7.4	0.0	1.1	5.9	0.4	0.7	0.0	0.7	0.4	20.9	0.0
49	32.5	3.3	14.3	12.0	3.8	9.1	9.6	0.0	1.4	0.0	0.0	0.5	1.9	0.0	11.5	0.0
50	30.4	1.2	12.6	8.3	3.5	5.6	0.4	1.2	0.0	0.0	1.6	1.6	16.5	0.0	17.3	0.0
52	32.6	5.3	15.9	10.1	4.0	6.5	0.0	0.0	0.9	0.0	0.0	1.3	0.0	0.9	22.5	0.0
54	24.3	9.9	12.9	10.7	9.0	4.7	0.0	0.0	3.8	0.0	0.9	0.0	0.4	0.4	23.1	0.0
56	24.7	1.4	11.4	8.5	2.6	2.5	4.4	0.0	39.5	4.1	0.4	0.4	0.4	0.0	0.0*	0.0
58	29.8	4.6	15.6	9.2	1.8	13.3	0.0	0.0	3.7	0.0	0.0	1.8	1.8	0.0	19.7	0.0
60	29.3	3.2	14.8	8.6	3.7	12.2	0.0	0.0	7.0	0.0	0.0	4.5	4.5	0.0	16.0	0.0
61	33.3	2.3	18.3	10.1	3.7	11.5	0.0	0.0	3.2	0.0	0.0	16.0	16.0	0.0	0.9*	0.0

Table 2. (cont.)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SS-62	26.0	2.0	22.0	2.5	4.5	12.5	0.0	0.0	5.0	0.0	0.0	0.5	9.5	0.0	5.5	0.0
66	32.6	7.3	17.6	6.9	5.6	8.6	0.0	0.0	1.7	0.0	0.0	0.0	3.0	0.0	16.7	0.0
68	40.2	2.5	10.5	5.9	0.8	6.6	0.0	0.0	15.9	0.0	0.0	0.0	7.5	0.0	10.0	0.0
70	29.0	3.5	8.5	11.5	2.5	25.5	0.0	0.0	3.0	0.0	0.0	0.0	9.5	0.0	7.5	0.0
71	28.2	3.8	17.3	10.5	3.4	5.5	0.0	1.3	9.7	0.0	0.0	0.8	2.1	0.0	17.3	0.0
72	31.8	2.3	19.6	9.8	2.8	4.6	0.0	0.0	1.9	6.1	0.0	0.0	2.3	0.0	18.7	0.0
74	32.2	1.7	17.8	10.8	2.6	6.5	0.0	0.4	0.9	0.0	0.0	0.0	8.3	0.0	18.7	0.0
75	34.1	2.8	22.7	10.6	2.9	6.3	0.0	0.0	1.9	3.4	0.0	0.0	2.4	0.0	11.0	0.0
76	30.5	5.2	18.3	8.5	4.2	12.7	0.0	0.0	4.2	0.0	0.0	0.0	2.3	0.0	13.6	0.0
79	32.2	4.8	18.2	11.4	3.8	8.4	0.0	0.0	3.8	0.0	0.0	0.0	7.6	0.0	7.6	0.0
80	33.5	4.6	11.6	9.8	2.8	10.3	0.0	0.0	2.3	0.0	0.0	0.9	4.7	0.9	18.6	0.0
84	27.8	0.8	16.2	8.5	4.5	9.8	0.0	0.0	9.4	0.0	0.0	0.9	4.9	0.0	17.0	0.0
87	27.8	3.2	18.3	8.5	5.7	7.3	0.0	0.0	2.9	0.0	0.4	0.4	0.8	1.2	23.3	0.0
88	30.9	3.8	9.2	6.7	0.8	6.7	4.2	4.2	13.3	3.3	0.8	0.8	0.4	5.0	10.0	0.0
90	32.6	1.7	16.1	10.4	2.2	5.2	0.0	2.2	6.5	0.0	0.0	0.4	0.0	1.7	20.9	0.0

Table 2. (cont.)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SS-91	27.8	1.8	7.7	3.6	0.0	2.3	0.0	38.6	0.0	0.0	0.5	0.0	0.0	0.0	17.7	0.0
92	35.5	1.7	20.7	11.5	5.1	6.5	0.0	0.0	0.4	0.0	0.0	0.4	0.8	3.0	14.0	0.0
94	34.3	4.0	20.5	12.0	4.0	6.7	0.0	0.0	0.0	0.0	0.0	1.8	1.3	0.0	15.2	0.0
97	36.1	3.2	18.0	10.8	3.0	7.1	0.0	0.0	3.2	0.0	0.0	1.3	1.1	1.1	15.1	0.0
98	35.1	5.0	16.5	7.1	4.7	7.9	0.0	3.5	0.4	0.0	0.4	0.0	1.2	1.2	15.0	1.2
99	31.5	2.2	16.5	6.7	1.3	3.1	0.0	14.2	8.9	0.4	0.0	0.9	0.9	0.0	14.7	0.0
100	30.0	2.1	15.6	11.0	0.8	4.6	0.0	3.4	4.2	0.8	0.0	0.0	0.4	0.0	27.0	0.0
101	29.8	1.2	21.1	11.8	1.2	12.6	0.0	0.0	4.7	0.0	0.4	0.0	10.6	0.8	5.9	0.0
102	28.0	3.4	16.3	10.3	3.8	8.7	0.4	0.0	0.8	0.0	0.0	1.9	1.5	0.0	18.6	0.0
104	33.0	1.7	11.7	9.6	3.3	5.4	0.0	10.8	6.7	0.8	0.4	0.4	1.7	2.9	11.7	6.1

Table 3. Modal Analyses, Barren Clastic Rocks (%)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SU-4	27.5	1.4	11.4	11.9	2.4	5.6	27.5	0.0	2.8	4.7	2.4	0.5	0.0	1.9	0.0	0.0
17	21.2	3.3	14.0	9.7	1.4	8.7	34.3	0.0	4.3	0.0	0.0	0.0	0.0	0.0	2.9	0.0
18	25.0	1.5	11.5	9.0	0.5	7.0	35.5	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.5	1.5
22	18.5	1.0	8.0	9.0	0.5	0.5	8.5	0.0	41.5	0.0	0.0	0.0	0.0	12.0	0.0	0.0
25	29.5	3.5	13.5	9.5	1.0	9.0	1.5	0.0	3.5	0.0	0.0	0.0	0.0	22.0	7.0	0.0
26	37.0	5.5	15.5	9.0	0.0	7.0	4.0	0.0	2.5	0.0	0.0	1.0	0.0	17.0	1.0	0.0
27	29.0	2.0	17.5	10.0	1.5	1.5	13.0	0.0	4.5	1.5	1.5	0.0	0.0	19.5	0.0	0.0
31	23.5	2.5	10.0	10.5	1.5	3.5	46.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
39	41.1	1.9	23.7	9.7	2.4	1.0	1.0	0.0	9.7	0.5	0.5	0.0	9.2	0.0	0.0	0.0
42	36.5	1.0	16.0	2.5	1.0	2.5	25.5	0.0	13.5	0.0	0.0	0.0	1.0	0.0	0.0	0.0
45	28.4	4.9	23.0	10.3	1.5	8.8	3.0	0.0	18.6	2.9	0.0	1.0	0.5	0.0	0.0	0.0
47	26.8	5.1	21.3	12.5	5.1	2.3	0.0	0.0	8.8	1.4	0.0	0.9	15.7	0.0	0.0	0.0
59	42.4	2.6	17.3	8.8	2.2	7.1	0.0	0.0	12.8	0.0	0.9	0.0	0.9	0.0	4.9	0.0
63	38.8	2.4	20.6	7.7	1.0	3.4	0.0	0.0	16.7	0.0	0.5	1.4	7.7	0.0	0.0	0.0
64	33.3	1.5	17.3	12.8	2.0	8.3	3.9	0.0	6.4	0.0	0.0	0.5	8.9	1.0	3.9	0.0

Table 3. (cont.)

Sample #	mq	pq	plg	o	mi	rf	cal cem	dol cem	hem cem	cly	hvy	mc	ps	mat	bit	all
SU-67	32.3	2.5	8.3	8.3	0.5	0.0	0.0	3.4	0.0	23.5	0.0	0.0	1.5	0.0	0.5	11.3
72	31.0	4.0	9.0	9.5	3.0	28.0	0.0	0.0	4.5	0.0	0.0	0.0	7.0	0.0	4.0	0.0
73	26.7	5.8	18.8	12.5	4.2	2.6	0.0	0.0	9.0	0.0	0.0	2.1	17.3	0.0	0.0	0.0
81	36.0	2.5	17.5	10.5	2.5	9.0	0.0	0.0	10.5	0.0	0.0	0.0	10.5	0.0	0.0	0.0
82	29.1	5.9	23.7	9.1	2.7	10.9	0.0	0.0	3.6	0.0	0.0	0.5	14.5	0.0	0.0	0.0
83	39.5	3.9	18.6	5.4	2.4	6.8	0.0	0.0	2.0	0.0	0.0	0.5	21.0	0.0	0.0	0.0
85	24.8	1.5	4.9	5.4	0.5	0.5	40.2	0.0	0.0	0.0	0.0	0.0	2.5	0.0	0.0	19.6
86	29.8	3.5	21.4	7.3	2.0	11.2	0.0	0.0	15.1	0.0	0.0	0.5	9.3	0.0	0.0	0.0
96	28.9	2.9	19.7	7.2	3.4	5.3	0.0	0.0	11.5	0.0	0.0	0.5	20.7	0.0	0.0	0.0
103	21.0	1.5	4.4	8.3	1.5	35.6	31.7	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.0	0.0

Table 4. Modal Analyses, Chemical Rocks (%)

Sample #	cal	dol	ost	ool	intra	mq	pq	plg	o	mi	rf	hem cem	ps	bit	other
SU-6	41.0	0.0	0.0	0.0	0.0	27.0	7.0	3.0	4.0	1.5	7.5	1.0	2.0	0.0	6.0
11	90.0	0.0	0.0	0.0	0.0	6.0	0.0	2.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	61.4	0.0	0.0	0.0	14.3	0.0	2.9	0.7	1.4	0.7	18.6	0.0	0.0	0.0
33	58.2	0.0	19.4	12.4	4.0	1.5	0.0	1.5	0.0	0.0	0.5	2.5	0.0	0.0	0.0
SS-35	1.0	75.0	2.0	6.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	13.0	0.0
36	0.0	14.0	22.0	39.0	1.0	2.0	0.0	2.0	0.0	0.0	0.0	0.0	8.0	12.0	0.0
48	55.3	0.0	0.0	0.0	0.0	19.8	0.0	8.4	6.4	0.0	1.0	0.0	1.0	5.9	2.0
55	0.0	38.0	1.0	30.0	16.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	9.0	1.0
SU-69	25.4	0.0	28.2	19.6	18.2	2.0	0.5	1.9	1.4	1.9	0.0	1.0	0.0	0.0	0.0
SS-78	0.0	30.0	56.0	1.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	4.0	0.0
SU-85	40.3	0.0	3.4	16.3	0.0	25.0	1.5	4.9	5.4	0.5	0.5	0.0	2.5	0.0	0.0
89	80.0	0.0	2.0	0.0	0.0	8.0	0.0	5.0	3.0	0.0	2.0	0.0	0.0	0.0	0.0

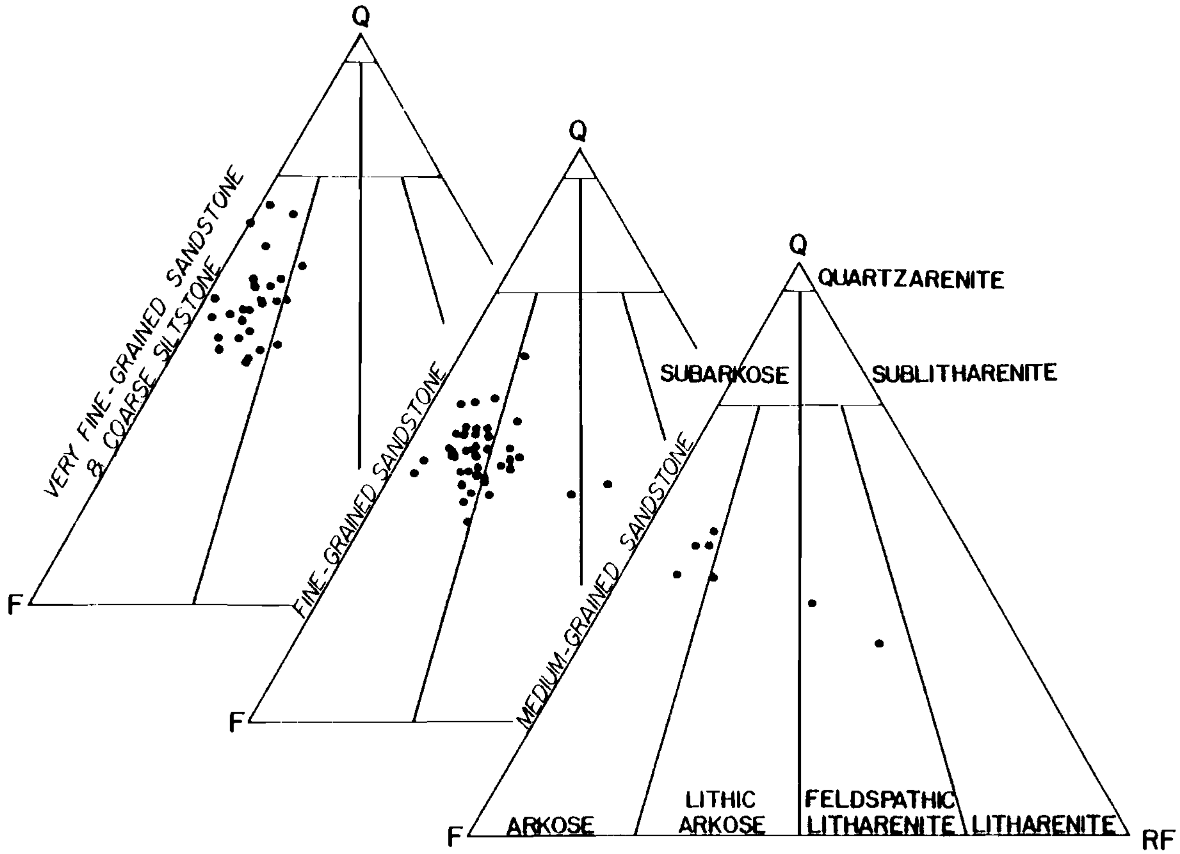


FIG. 10.--Compositions of framework constituents in clastic rocks of the Sunnyside oil-impregnated sandstone deposit. Classification after Folk (1968).

quartz-feldspar ratio in the three groups is essentially unaffected by mean grain size variation, whereas the fraction of rock fragments increases with grain size and is responsible for the compositional variation between the groups (Fig. 11).

Quartz is the most abundant framework constituent. These rocks, however, are characterized by an unusually high percentage of feldspar, which rarely exceeds quartz in total percent. The abundance of rock fragments ranges from 5-32%, and averages 11% of the total rock composition. The average sandstone (Tables 2 and 3) contains 49% quartz, 40% feldspar and 11% rock fragments.

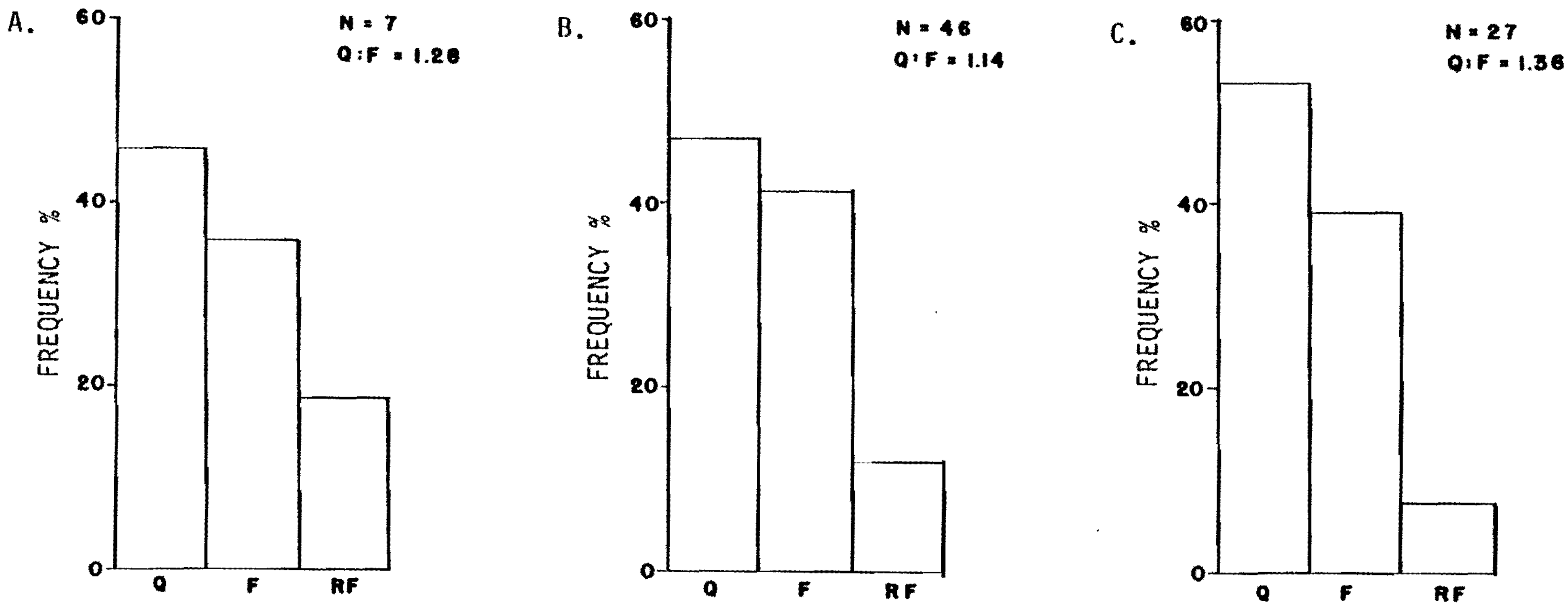
Terrigenous rocks are classed as one of three rock types; arkose, lithic arkose or feldspathic litharentie. Arkose is the most common sandstone type and feldspathic litharenite the least common. As mean grain size increases the range of compositions becomes greater.

There is no petrographic difference between the barren and oil-impregnated rocks of equivalent grain sizes.

The carbonate rocks were classified according to the scheme of Folk (1962). A variety of carbonate rock types are present within the oil-impregnated section at Sunnyside, varying from calcareous to dolomitic and from orthochemical to allochemical.

Quartz

As in most clastic rocks, quartz is the most abundant detrital mineral present in the sandstone and siltstone at Sunnyside. To study the occurrence of quartz varieties, quartz was classified according to optical properties as monocrystalline or polycrystalline. Blatt and Christie (1963) suggest the efficacy of further subdivision



Q = Quartz, F = Feldspar, RF = Rock Fragments, including chert

FIG. 11.--Average composition of Sunnyside sandstone. A. Medium-grained sandstone. B. Fine-grained sandstone. C. Very fine-grained sandstone and coarse siltstone. Classification after Folk (1968).

of monocrystalline quartz into nonundulatory and undulatory (extinction angle > 5°) varieties. Polycrystalline quartz is subdivided into two categories according to the number of individual crystals per grain, 2-3 crystals per grain or >3 crystals per grain (Basu and others, 1975). The occurrence and character of quartz is summarized in Figures 12 and 13.

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Monocrystalline nonundulatory quartz is the most common quartz type (Fig. 12). Nonundulatory quartz has relatively few inclusions and/or vacuoles and only rarely does quartz contain an abundance of needles, microlites or vacuoles.

The occurrence of polycrystalline quartz is to a large degree a function of grain size (Connolly, 1965; Blatt, 1967a; and Anderson and Picard, 1971). This trend of decreasing polycrystalline quartz with a decrease in grain size is present in the clastic rocks studied. The percent monocrystalline quartz versus polycrystalline quartz increases from 88.8% in the 1-2 phi size class, to 91.9% in the 2-3 phi size class, and to 92.8% in the 3-5 phi class.

The significance of quartz types in provenance determination has been addressed by several authors (Krynine, 1949; Blatt and Christie, 1963; Blatt, 1967b; Folk, 1974; and Basu and others, 1975). Krynine (1949) developed a genetic classification of quartz types. "Common quartz" (nonundulatory) with few inclusions and vein quartz is thought to be characteristic of an igneous source and undulatory, stretched or schistose (polycrystalline) quartz showing preferred orientation is attributed to a metamorphic origin. Volcanic quartz is clear, contains very few inclusions, and is often embayed. Folk

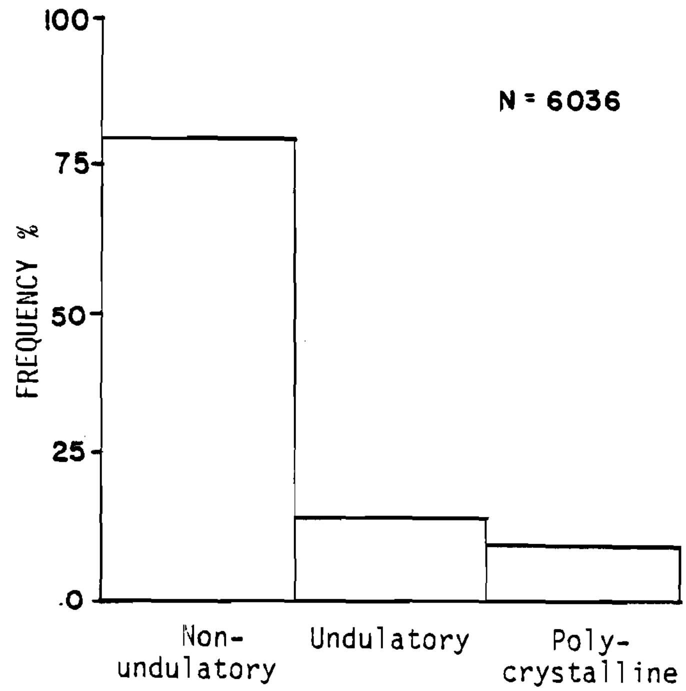


FIG. 12.--Quartz extinction types in Sunnyside clastic rocks.

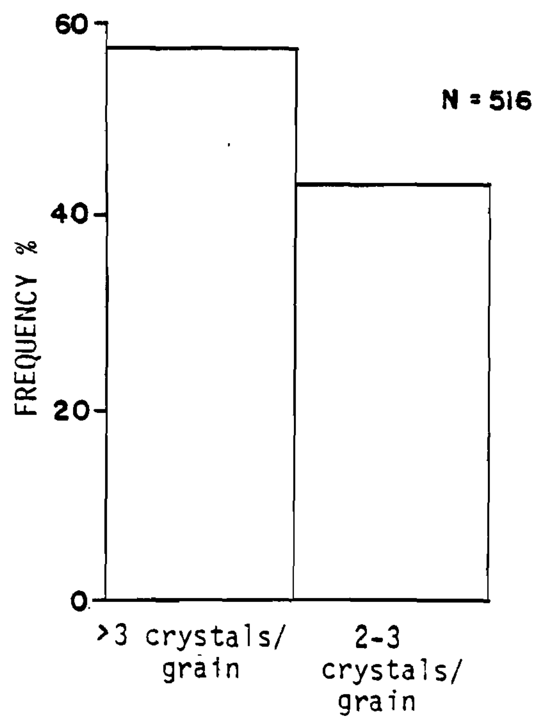


FIG. 13.--Distribution of number of crystals in polycrystalline quartz grains in Sunnyside clastic rocks.

(1974) developed an empirical classification of quartz based on the optical properties and inclusions of individual grains. The types and abundance of inclusions, vacuoles, microlites and needles are believed to be diagnostic of particular source terranes. The stability of detrital quartz has been shown to be related to quartz types (Blatt and Christie, 1963). Nonundulatory quartz is more stable than undulatory and polycrystalline quartz in the sedimentary cycle. The result is an enrichment of nonundulatory quartz in a mineralogically mature sandstone.

Basu and others (1975) found that the degree of polycrystallinity of quartz is related to the original source rock. They used the relative occurrence of two categories of polycrystalline quartz, 2-3 crystals per grain and >3 crystals per grain, along the abundance of undulatory and nonundulatory quartz as an aid in provenance interpretation. Figure 14 illustrates the variable plots of medium- and fine-grained rocks on the diamond diagram developed by Basu and others (1975). The majority of samples lie near the division between plutonic and high and middle rank metamorphic zones. This is indicative of a source terrane of these types for the given quartz population, if this population was completely composed of first cycle clastic quartz grains. The presence and abundance of sedimentary rock fragments and rounded character of many of the quartz grains indicate a second or multi-cycle origin for some of the detrital quartz, in particular, the nonundulatory variety. Determination of the amount of recycled quartz contributed by sedimentary rocks is difficult. The method of Basu and others (1975) is therefore of

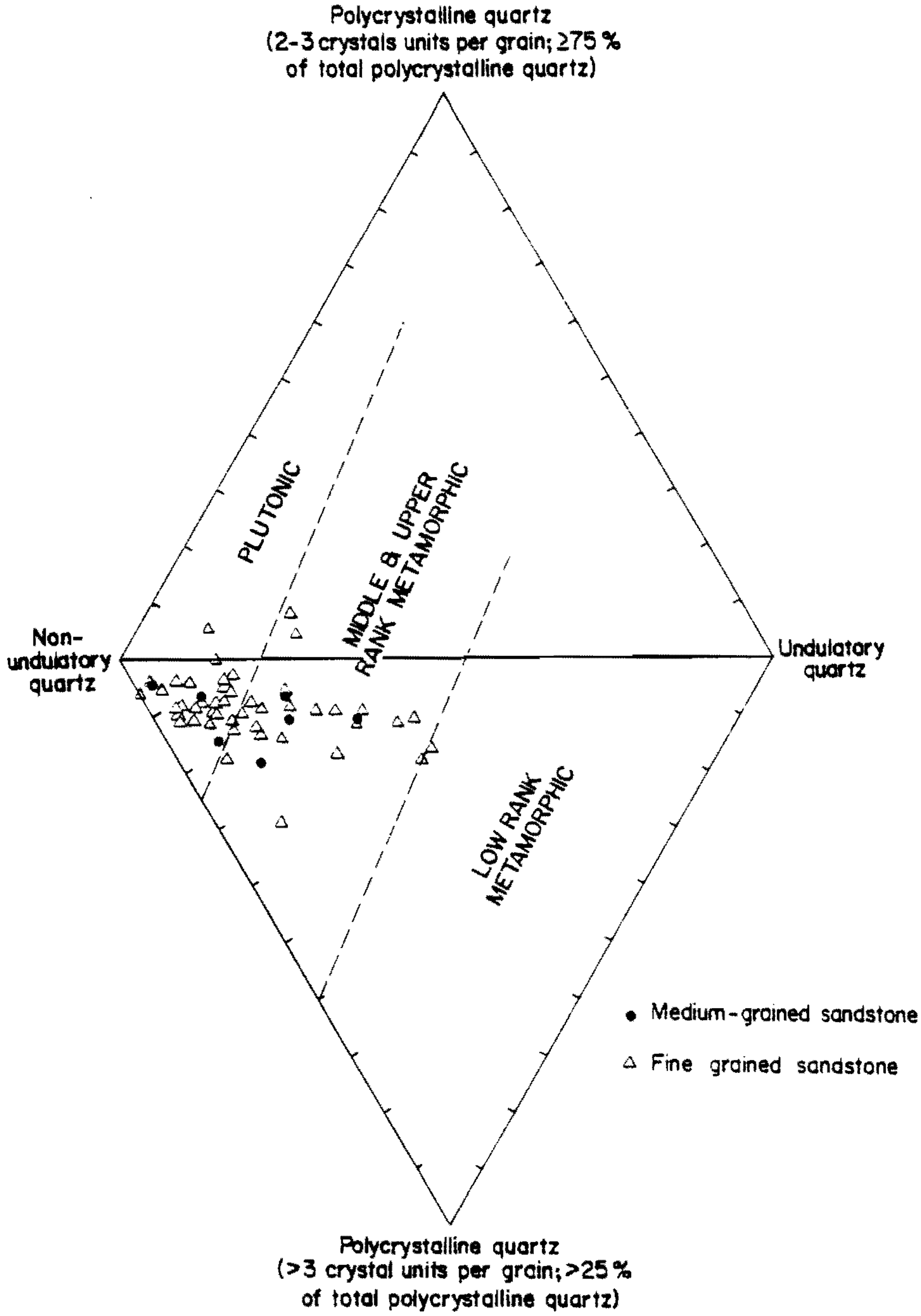


FIG. 14.--Four variable plot of quartz varieties in medium- and fine-grained sandstone from the Sunnyside area. Classification adapted from Basu and others (1975).

limited usefulness in interpreting rocks of mixed provenance, crystalline and sedimentary, as in this case. It does provide a limit though, to the type of terrane providing primary detritus. In most cases, a shift toward the undulatory quartz end-member can be expected if the masking effect of the reworked quartz population could be removed.

Feldspar

Feldspar is the second most abundant mineral, averaging 28%, and ranging up to 35% of the total rock fraction. Rarely, it exceeds quartz in abundance. Jacob (1969) and Picard and others (1973) note a similar compositional trend in the laterally equivalent delta facies and black shale facies, respectively, of the Green River Formation. Four major feldspar varieties were distinguished. The relative abundance of each variety (Fig. 15) is: Na-plagioclase > orthoclase $\gtrless$ microcline > microperthite.

Na-plagioclase is the dominant feldspar variety and is almost twice as abundant as orthoclase. Grains are angular to subrounded and occur in all stages of decomposition from fresh to almost completely altered. Strongly etched plagioclase is common in oil-impregnated sandstone where the pore spaces were created by dissolution of the plagioclase grains. Untwinned plagioclase is more abundant than twinned plagioclase (Fig. 16). The ratio of untwinned plagioclase-twinned plagioclase is a function of grain size and increases with a concomitant decrease in grain size (Fig. 17). Albite twins are the most abundant plagioclase twins. No combined Albite-Carlsbad twins were observed and only rarely is plagioclase

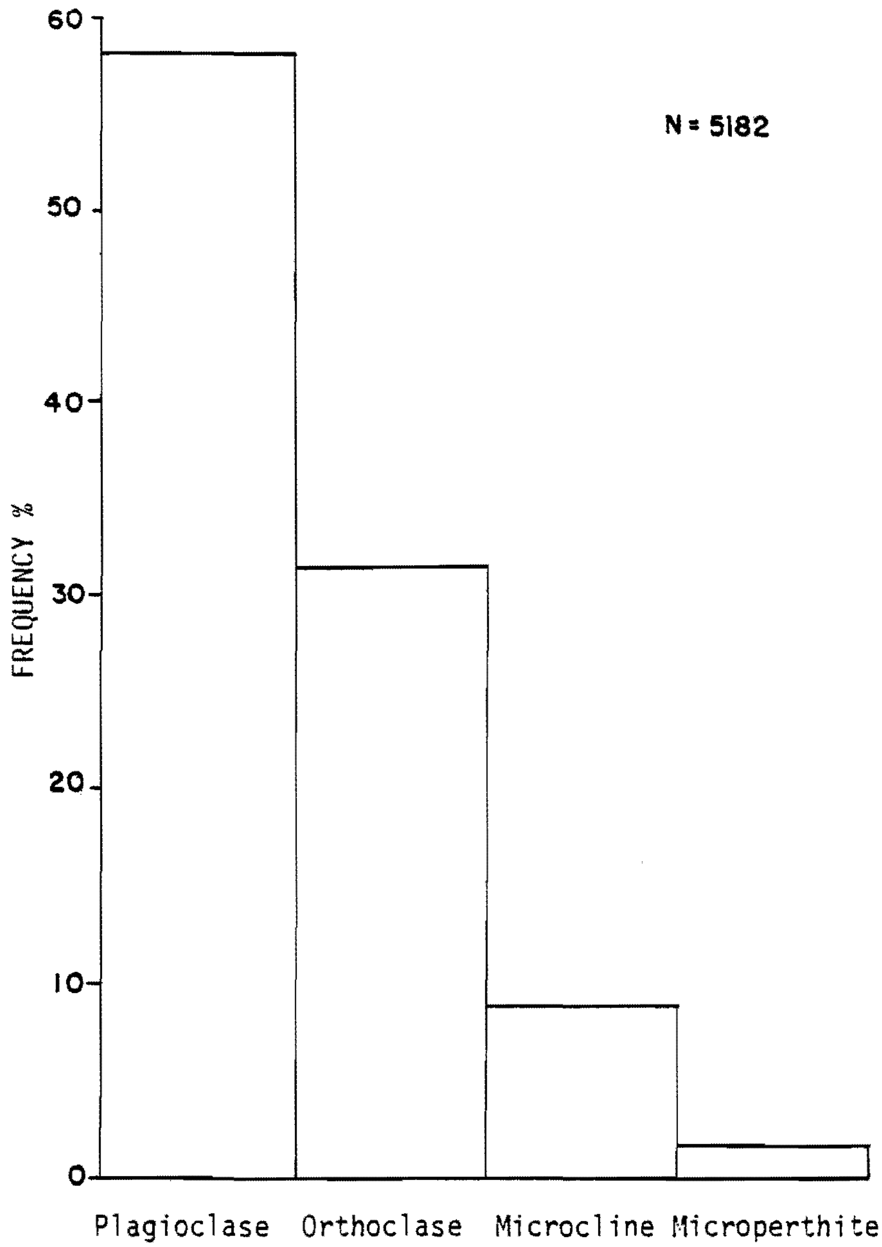


FIG. 15.--Abundance of feldspar species in Sunnyside clastic rocks.

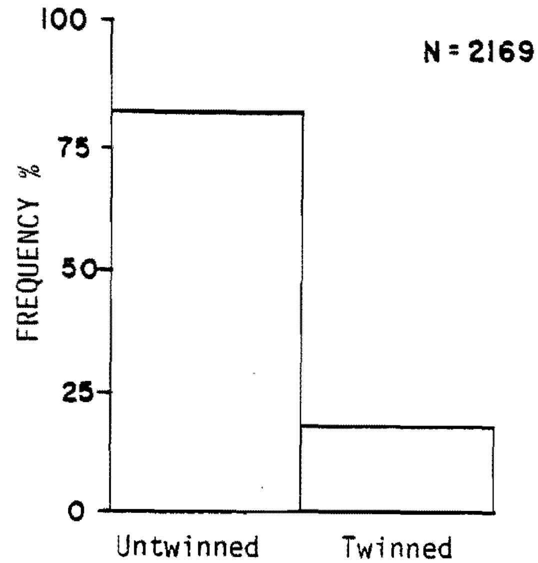


FIG. 16.--Plagioclase twinning types.

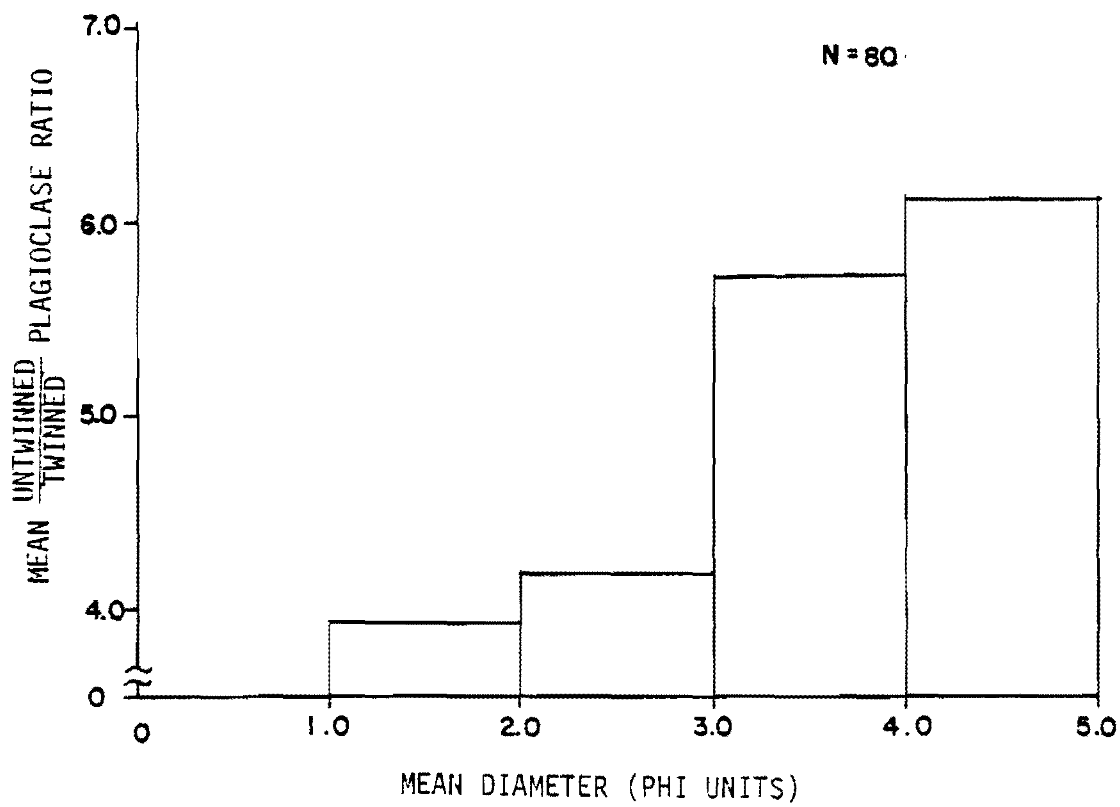


FIG. 17.--Variation of untwinned/twinned plagioclase ratio with grain size.

twinned according to the Carlsbad law. This could be a result of breakage along twin and composition planes during stream transport where Carlsbad twins tend to be destroyed relative to Albite twins (Pittman, 1969).

Authigenic plagioclase overgrowths are, almost without exception, present on every detrital plagioclase grain. The overgrowths often completely surround the original plagioclase grain and are clear, in contrast to the cloudy, weathered, detrital grain. Overgrowths on twinned plagioclase grains maintain continuity with the twin lamellae, but are compositionally distinct (Fig. 18), being almost pure albite, as determined by microprobe analysis (Fig. 19, and Appendix B). The pure Na end-member composition of authigenic plagioclase is common in sandstone (Kastner, 1970, p. 591; Pettijohn and others, 1973, p. 38; Pettijohn, 1975, p. 204; and Trevena and Nash, 1981, p. 138). The overgrowths, when viewed with the scanning electron microscope (Fig. 20), often exhibit distinct crystal faces and interlocking of adjacent overgrowths, which decreases porosity.

Zoning in plagioclase may be indicative of distinctive source terranes (Pittman, 1963, 1969 and 1970). Oscillatory zoning is the common mode of zoned volcanic plagioclase. Igneous plagioclase, when zoned, exhibits normal or reverse zoning, whereas metamorphic plagioclase is over 95% unzoned and never exhibits oscillatory zoning (Pittman, 1963). Zoning in the plagioclase is rare in the sandstone and siltstone at Sunnyside. No oscillatory zoned plagioclase was observed.

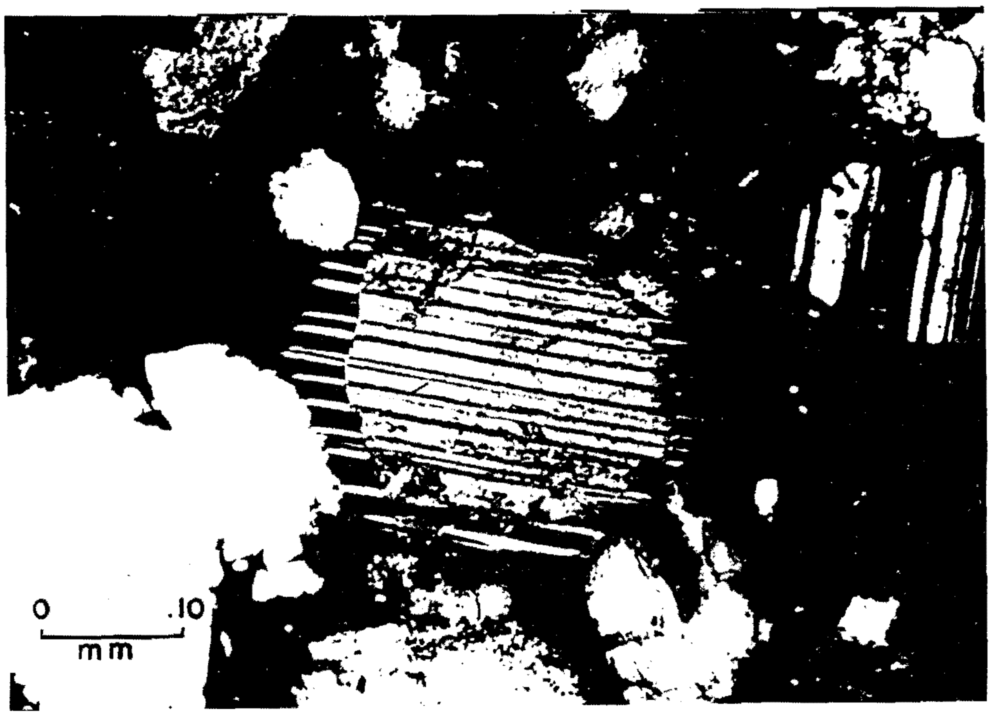


FIG. 18.--Twinned Na-plagioclase detrital grain with authigenic albite overgrowth. Twin lamellae of overgrowth maintain continuity with grain lamellae. Differing extinction angles between grain and overgrowth due to compositional variation. Cross-nicols.

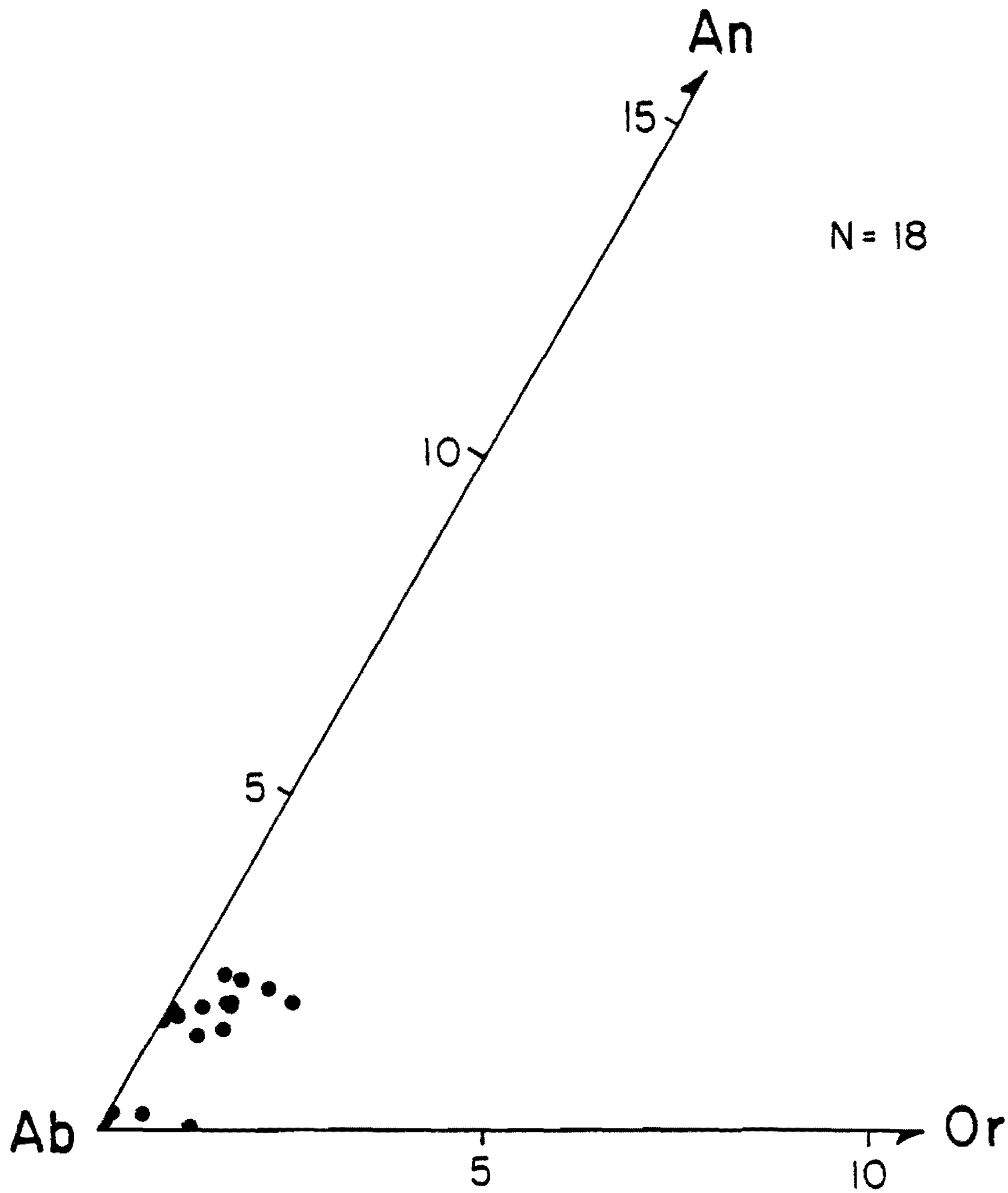


FIG. 19.--Microprobe analysis of feldspar overgrowths (mole %).

FIG. 20.--Authigenic albite overgrowth. Incomplete infill (center) and interlocking of individual grain overgrowths (bottom right) are evident. SEM - 440x.

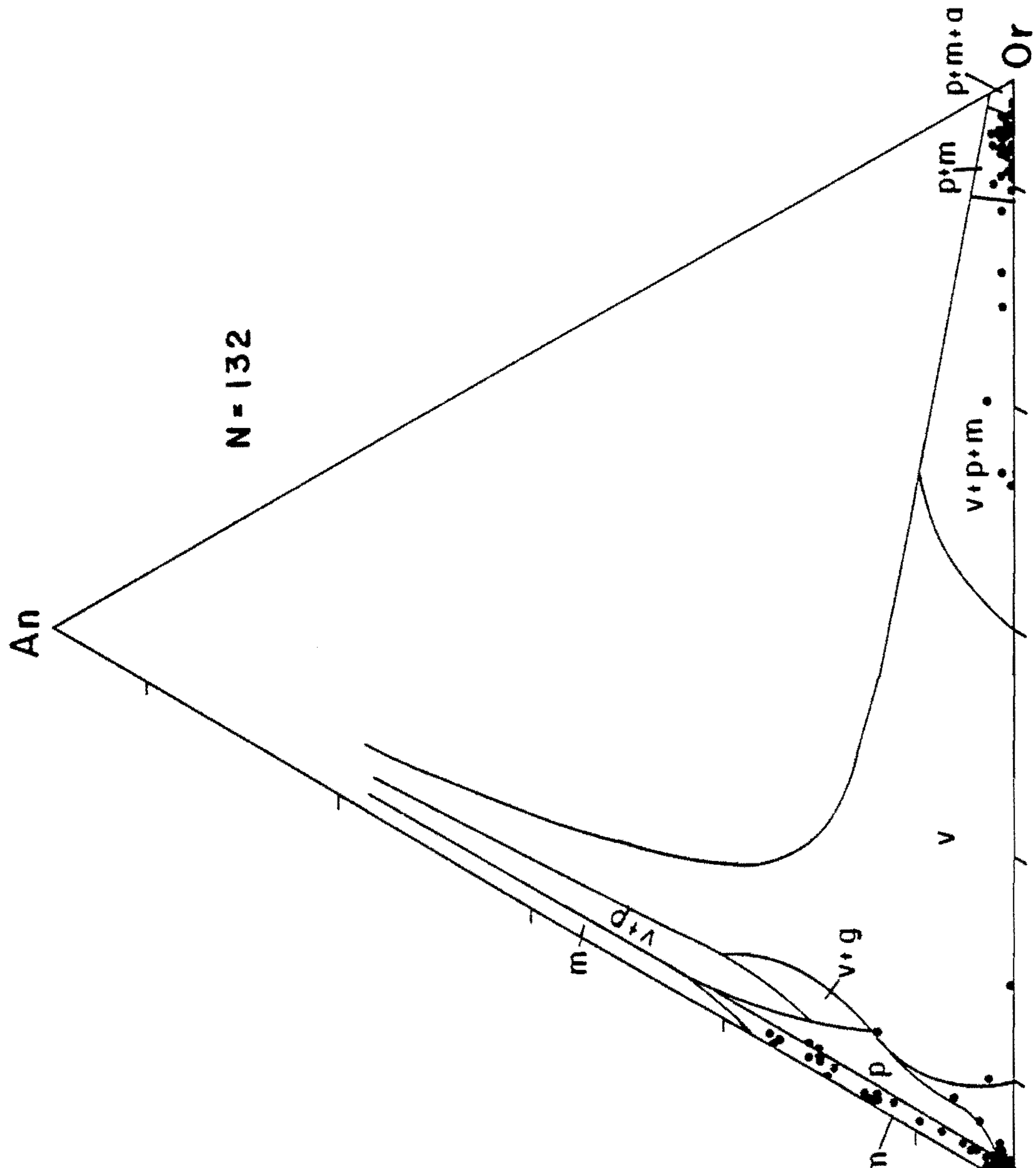
Staining of the K-feldspar (Friedman, 1971) readily distinguishes them from plagioclase. Potassic feldspar grains are angular to subrounded and clear to slightly weathered. Orthoclase is the most abundant K-feldspar. Twinned orthosclase is rare but, when present, occurs as Carlsbad twins. Microcline exhibits the typical grid-and spindle-type twinning. Microperthite is the least abundant feldspar species. Overgrowths on potassic feldspars were not observed during modal analysis.

Compositional analyses of detrital feldspar grains in five oil-impregnated sandstones were obtained by microprobe analysis. The An, Or, and Ab mole percent of each analysis is presented in Appendix B. The five samples (SS-84, SS-87, SS-90, SS-92, SS-54) are distributed vertically through the oil-impregnated section (refer to Fig. 1). There is no significant vertical change in the distribution of the feldspar species upward through the oil-impregnated section.

The composition of 132 detrital feldspar grains is illustrated in Figure 21. Feldspar compositions average 60% Na-plagioclase and 40% potassic feldspar. This distribution is similar to the feldspar distribution of 58% Na-plagioclase and 42% potassic feldspar obtained by petrographic point counting. Na-plagioclase ranges from albite to oligoclase with the highest percentage albitic in composition. The K-feldspar is highly potassic.

Superposed upon the feldspar ternary diagram (Fig. 21) are the boundaries of the compositional range of diagnostic provenance groups (Trevena and Nash, 1981, p. 138). The majority of analyses plot within the plutonic and metamorphic fields. Only three analyses plot

FIG. 21.--Composition of detrital feldspar (mole %) in five samples of Sunnyside oil-impregnated sandstone. Boundaries of compositional range of seven provenance groups of feldspar from Trevena and Nash (1981, p. 138) . v - volcanic; p - plutonic; m - metamorphic; g - granophyre; a - authigenic.


An
Ab
Or
N = 132
v
v+p
v+g
v+p+m
p
p+m
p+m+a
m

outside the plutonic and metamorphic range and they are within the volcanic field. The distribution of feldspar compositions is similar to that of and unnamed Eocene(?) deposit in New Mexico, also believed to be non-volcanic in origin (Trevena and Nash, 1981, p. 141, Fig. B).

Rock Fragments

Rock fragments average 8% of the total rock fraction and occur in trace amounts in siltstone and range up to 35% in medium-grained sandstone. Four categories of rock fragments were distinguished during modal analyses; clastic, igneous and metamorphic, chert and carbonate (Fig. 22).

Sedimentary rock fragments are the most abundant fragment types. Clastic rock fragments are composed of brownish to reddish claystone and shale. They are rounded to subrounded, but often ductilely deformed due to compaction. In oil-impregnated sandstone the clastic rock fragments are saturated with bitumen, which imparts a darker color to the fragments. Clastic rock fragments finer than silt-size were not observed. Chert grains, commonly derived from limestones (Folk, 1974, p. 81), are ubiquitous in all the clastic rocks averaging 20% of the rock fragment population. Several varieties were observed and, in order of abundance, are: 1) brownish, equicrystalline chert with hematite and opaque inclusions; 2) clear, equicrystalline chert; 3) clear, subsequant crystalline chert. No chalcedony was observed in the rocks studied. Carbonate rock fragments, present only in medium- and fine-grained sandstone, are micrite and silty micrite. Many of the carbonate rock fragments may be intraformational in origin.

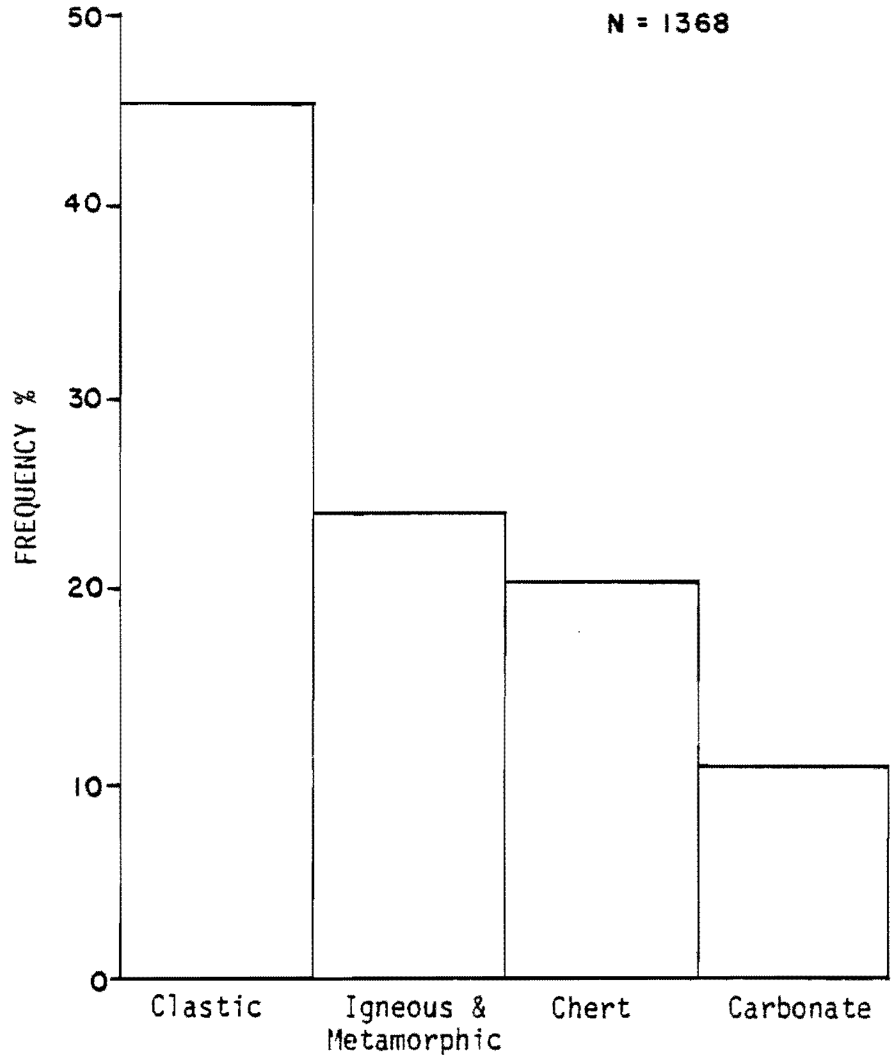


FIG. 22.--Abundance of rock fragment varieties in Sunnyside clastic rocks.

A variety of igneous and metamorphic rock fragments are present; plutonic, middle to upper rank metamorphic, and volcanic. Plutonic rock fragments are equant to subequant crystalline composites of quartz, K-feldspar, and plagioclase. The plagioclase occassionally exhibits myrmekitic intergrowths of quartz. Metamorphic varieties consist of quartzo-feldspathic gneiss fragments and occasionally schistose(?) rock fragments. Volcanic rock fragments, which are very rare, are composed of semi-aligned feldspar laths in an aphanitic ground mass.

The heterogeneous assemblage of rock fragments is evidence of a mixed provenance. Sedimentary rock fragments are not resistant to abrasion, thus selectively destroyed during transport (Folk, 1974, p. 90). The high percentage of sedimentary rock fragments indicates a brief transport distance, and therefore a relatively close sedimentary source. The durability of metamorphic rock fragments is variable. Gneissic fragments are more resistant to abrasion and weathering than phyllitic or schistose fragments. The majority of metamorphic fragments are gneissic. This may indicate the selective destruction of the softer, micaceous schistose fragments during transport and a greater distance of transport for the igneous and metamorphic fragments than the sedimentary fragments.

A minor amount of volcanic rock fragments are present in the rock studied. The soft nature and susceptability to weathering of volcanic rock fragments precludes a lengthy stay in the sedimentary cycle. Major volcanic activity occurred during Eocene time in southwestern Colorado and northwestern Wyoming, the San Juan and Absaroka volcanic fields, respectively. Evidence of major volcanic contribution to the Green River Formation is not recorded until the deposition of the Parachute and Evacuation Creek members which are younger than the oil-impregnated sandstone at Sunnyside. The San Juan volcanic field is favored as the source of the volcanic material by Picard (oral comm., 1981).

Major volcanic activity in the San Juan region did not occur until after deposition ofthe rocks at Sunnyside. However, continuous, if only minor, volcanic activity in the San Juan region during Paleocene time (Edwards, 1966) may have provided a small amount of volcanic material to the fluvial system draining the area.

Heavy Minerals

Minerals with a specific gravity greater than 2.95 are considered heavy minerals. The presence of heavy mineral species and estimates of relative abundances within the fine- to very fine-sand fraction are important to this study.

Heavy minerals make up less than 1% of the total rock fraction. Opaque and nonopaque minerals are present; however, only nonopaque minerals were considered during analysis. Heavy minerals were divided into three groups: 1) Mica; 2) Ultrastable, which contains zircon, tourmaline and rutile; and 3) Metastable, which contains garnet, hornblende, clinozoisite, apatite, sphene, staurolite, and monazite.

Mica - Muscovite is abundant and widespread in the clastic rocks studied and occurs as irregular basal flakes. There is a conspicuous absence of biotite in the Sunnyside sandstone. Only a green, slightly pleochroic variety of biotite was rarely observed in the heavy mineral separates and brown, pleochroic biotite was observed in only one thin section.

Ultrastable - Zircon is the most abundant ultrastable heavy mineral. A varietal suite of zircon, differing in color and morphological appearance, is present. Colorless and pink to purple zircon occurs as well-rounded, weathered crystals, which are often coated with hematite, and euhedral, unweathered crystals. Beveridge (1960) suggests a Precambrian source for purple-colored zircons.

Tourmaline is a common heavy mineral which occurs in a variety of colors and shapes. Two distinct suites of tourmaline are present in the sandstone at Sunnyside. The first suite is characterized by rounded tourmaline grains with a pleochroic scheme of clear, light brown, or reddish brown to very dark brown or very dark reddish brown. The second suite has a pleochroic scheme of light brown or reddish brown to very dark green. The grains are angular and occur as euhedral crystals, which are often broken. The angular suite of tourmaline is more abundant than the rounded suite. Two distinct tourmaline suites are suggestive of a contribution of reworked heavy minerals from sedimentary rocks and a first cycle contribution of heavy minerals from crystalline rocks.

A minor amount of sphene, which occurs as yellowish-brown, angular grains, is present. The minor amount of this common ultra-stable heavy mineral may be a function of the sand size fraction used for analysis.

Metastable - Many metastable heavy minerals are present in the sandstone. The most abundant are garnet and clinozoisite, with apatite, hornblende, staurolite and monazite present in subordinate amounts. Garnets are identifed by their etched grain surface and isotropic nature. Almandite, a clear variety of garnet common in metamorphic rocks (Kerr, 1959), was the only variety observed Hornblende is rarely present in the heavy mineral separates. It is, however, common in barren sandstone with a high percent matrix where it occurs as bright green, pleochroic, angular grains. Hornblende was not seen in the thin sections of oil-impregnated sandstone. Clinozoisite (iron-free epidote) is present as translucent, subround grains, which exhibit minor signs of etching. The common occurrence of clinozoisite is in middle rank metamorphic rocks (Kerr, 1959). Minor metastable mineral observed are apatite, present as clear, rounded to subangular grains; staurolite, present as subrounded grains to euhedral crystals; and monazite, of which only one grain was observed. Monazite and apatite occur in acidic igneous rocks, but apatite may also occur in middle to high rank metamorphic rocks, as does staurolite (Hubert, 1971).

The conspicuous absence of hornblende and biotite from the high porosity rocks is an important aspect of the heavy mineral analysis. The implication of their absence will be discussed in the section concerning cement types.

Interpretation - Suites of heavy minerals may often be identifed as diagnostic of distinct terranes. A mixed provenance of sedimentary and crystalline sources for the rocks at Sunnyside is reflected in the heterogeneous assemblage of heavy mineral grains, in particular, zircon and tourmaline.

Denson and Chisholm (1971) studied heavy mineral assemblages of Tertiary formations throughout the Rocky Mountain region. Their results show that the Paleocene epoch is characterized by rounded tourmaline and purple zircon, reworked from Paleozoic and Mesozoic sedimentary rocks. The uplift and uncovering of Precambrian rocks in the Rocky Mountain region is reflected in Lower Eocene rocks by the appearance of epidote, blue-green hornblende and garnet. Volcanic assemblages of green to brown hornblende, augite and euhedral, colorless zircon appear in Upper Eocene rocks. The heavy mineral assemblage at Sunnyside is similar to that described for Lower Eocene rocks.

Allochemical Constituents

Fossils constitute the largest percentage of allochemical constituents. Ostracode carapace fragments are present in the sandstone, but are more abundant in carbonate rocks. Ostracodes in sandstone are partially to completely replaced by hematite, whereas in carbonate rocks the ostracodes are dolomitic. Pore spaces in the carapaces, due to either incomplete infilling of the carapaces upon deposition or secondary pore space development, are often filled with bitumen. Algal beds are present in minor amounts. Bradley (1929a, p. 207) has identified the algae of the Green River Formation as Chlorellopsis coloniata Reis. The algal material occurs as locate reef colonies in the Sunnyside area.

Oolites occur as isolated allochems in sandstone and are abundant in carbonate rocks. Concentric oolites in various stages of development which contain nucleii of carbonate grains and clastic grains are present. The oolites are dolomitic and often show patchey development of dolospar which has recrystallized from a carbonate nucleus. Organic material, and occasionally bitumen, impart a dark brown color to the oolites.

Intraclasts, micrite to silty micrite in composition, are associated with oolites and ostracodes. They are subrounded to rounded and occasionally coated with hematite.

Cement

Calcite, dolomite and hematite are major authigenic pore-filling cements. Authigenic quartz and feldspar overgrowths act as cementing agents when individual grain overgrowths are intergrown. Minor developments of authigenic clay was detected by petrographic analysis and identified as smectite and K-mica by X-ray analysis. The relative abundances of cement varietites on oil-impregnated and barren rocks are shown in Figures 23 and 24.

Barren sandstone and siltstone averages 11% calcite and a trace of dolomite cement. In some cases, sandstone contains over 50% sparry calcite cement and is classed as sandy sparite. Calcite commonly occurs as sparry mosaic porefilling cement. Poikilotopic calcite cement is present, but calcite crystals are generally equal to or smaller than the individual clastic grains. Dolomite occurs as spar-size rhombs distributed throughout the barren sandstone.

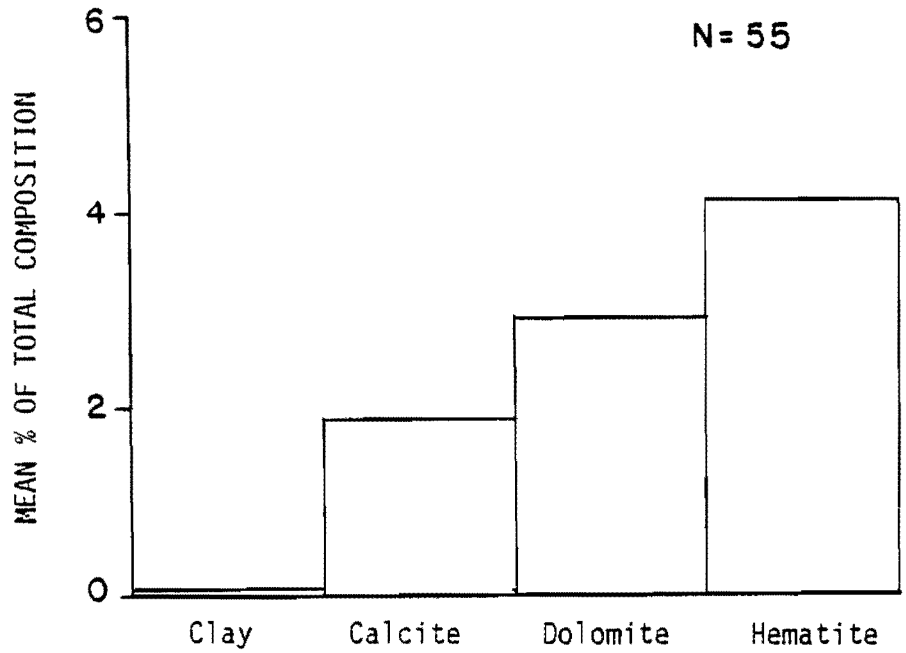


FIG. 23.--Distribution of cement varieties as mean percent of total rock composition in Sunnyside oil-impregnated clastic rocks.

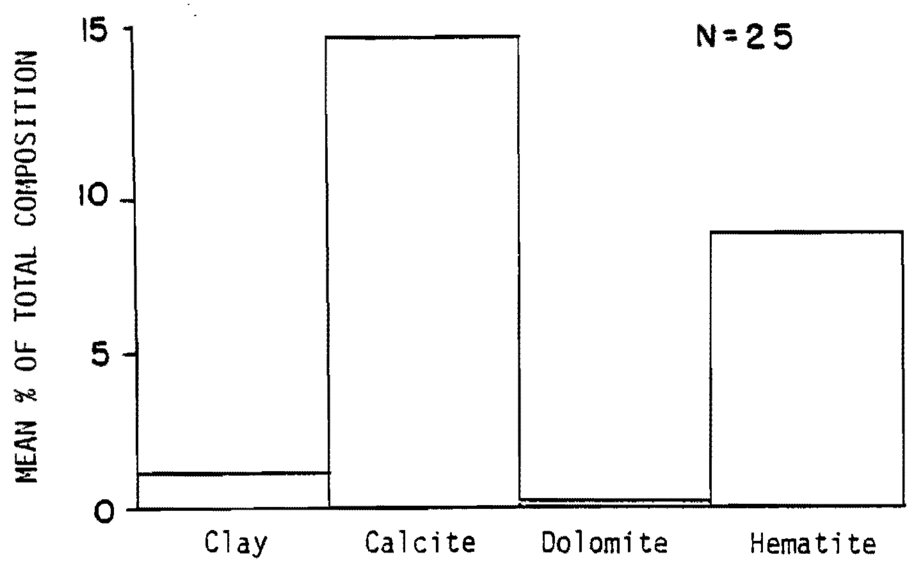


FIG. 24.--Distribution of cement varieties as mean percent of total rock composition in Sunnyside barren clastic rocks.

Oil-impregnated sandstone and siltstone average 2.0% calcite cement and 3.0% dolomite cement. Dolomite is present as spar-size dolomite rhombs, similar to those in the barren clastic rocks, as microcrystalline dolomite and rarely as overgrowths on dolomite rhombs. Sparry calcite occurs as a very patchey pore-filling cement randomly distributed through out the sandstone.

Hematite occurs in barren and oil-impregnated rocks, coating grains, filling pore spaces, and replacing fossil fragments and dolomite rhombs. Hematite averages over 4% of the total rock fraction in oil-impregnated clastic rocks and 8% in barren clastic rocks. Rarely, hematite is so well-developed that it completely fills pore spaces and comprises over 15% of the total rock fraction.

Two major theories of the origin of red beds address the problem of the source of the hematite pigment. Walker (1963 and 1967), Picard (1965) and Van Houten (1965 and 1968) support a post-depositional origin of hematite pigment formed by the in situ alteration of Fe-bearing minerals. Krynine (1949) supports the theory of a primary detrital origin for the hematite in red beds.

Walker (1963 and 1967) believes the major source of the hematite pigment is from the decomposition of Fe-silicates, in particular hornblende and biotite. The high porosity sandstone at Sunnyside rarely contains hornblende and biotite. They occur only in barren sandstone with a high percentage of matrix material, where they are the most abundant heavy minerals. The presence of biotite and hornblende in rocks with very low primary porosity substantiates their presence in the original heavy mineral population. Their absence in high porosity and well-cemented sandstone suggests the decomposition of these Fe-silicates is partially due to intrastratal solution which altered them to hematite.

Porosity and Bitumen

Porosity of sandstone and siltstone ranges from less than 1% to greater than 20%. The average porosity of the 29 oil-impregnated sandstones analyzed for percent bitumen by weight is 17.7% and the average porosity for barren sandstone is 6.5%. Rock samples were impregnated with epoxy, because of their friable nature, to prevent bitumen from washing out during preparation, and to aid in the identification of pore spaces during modal analysis.

Relationship Between Texture and Bitumen

The primary textural features, mean grain size and sorting, affect the original degree and character of the porosity of a rock. The diagenetic processes of cementation, compaction, and dissolution or replacement of detrital grains modify the original porosity and permeability.

Carrigy (1962) studied the effect of texture on the distribution of bitumen in 132 samples of Athabasca oil sands in Alberta, Canada. Median diameter and fraction of clay-size material were the variables he chose to represent texture. Regression analysis of the relationships between median diameter (phi units) and arcsin $\sqrt{\text{fraction of clay-size material}}$ with percent bitumen by weight of each sample indicates a direct relationship between the variables.

Thirty samples of oil-impregnated rocks from the Sunnyside area were refluxed with toluene vapors to determine the percent by weight of bitumen in each sample (refer to Appendix A). The distribution of bitumen content by weight of the 30 samples, 29 terrigenous and 1 chemical, is shown in Figure 25. The mean grain size and fraction of silt- and clay-size material for each terrigeneous sample is presented with refluxion data for each sample in Table 5.

The Sunnyside oil-impregnated sandstone exhibits a weak correlation between the textural parameters, a mean grain size and fraction of silt- and clay-size material, and percent bitumen by weight (Figs. 26 and 27). No direct relationship exists between bitumen content and porosity of the sandstone (Fig. 28). Therefore, the effect textural properties of the sandstone have on bitumen content is minimized by the incomplete bitumen saturation of effective pore space. Bitumen often forms only a thin coating on detrital grains and is absent from the remaining pore space (Fig. 29). A SEM photomicrograph of an oil-impregnated sandstone (Fig. 30) illustrates in three-dimensions the incomplete saturation of pore spaces by bitumen. Prior to migration of petroleum, the pore spaces of reservoir rocks are commonly water-saturated. Displacement of pore fluids by migrating petroleum is never complete (Tissot and Welte, 1979, p. 323), which leads to incomplete saturation of pore spaces. Pore fluids in the oil-impregnated sandstone at Sunnyside were probably lost after uplift and exposure to the surface.

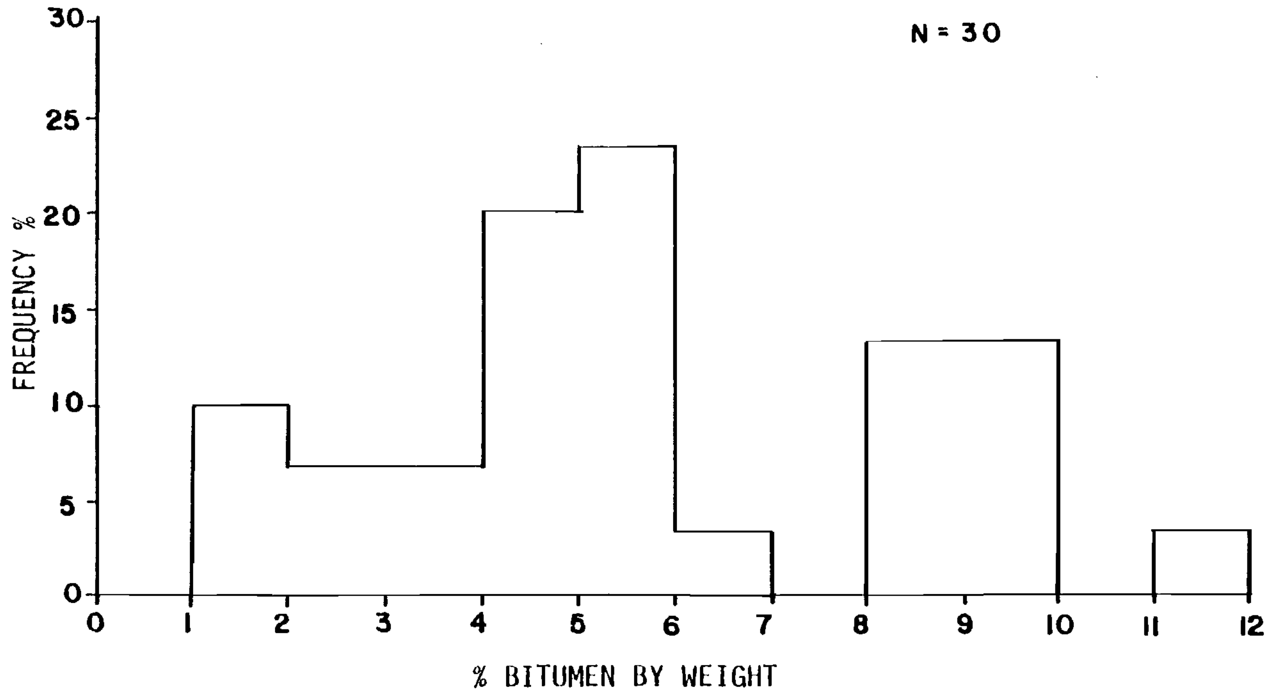


FIG. 25.--Distribution of percent bitumen by weight in 30 samples of oil-impregnated rocks from the Sunnyside deposit.

Table 5.--Refluxion and Textural Data for Selected Oil-Impregnated Rocks

Sample #	% Bitumen by Weight	Mean Grain Size (M_z)	Fraction of silt and clay
SS - 7	2.2497	2.13	.035
28	8.4476	2.58	.025
29	9.2958	2.66	.005
30	9.3201	3.37	.227
46	5.7962	2.77	.032
49	5.1400	2.11	.004
52	8.7633	1.87	.000
54	6.2332	2.04	.005
55	1.3711	---	----
56	5.3987	3.82	.340
60	11.5430	2.74	.015
61	8.7633	1.89	.000
62	2.0462	2.14	.000
68	3.0124	1.87	.025
70	1.1669	1.78	.000
71	4.8494	2.84	.025
74	5.5914	2.33	.015
75	4.7278	2.28	.000
76	5.0887	2.25	.000
80	4.8898	2.65	.000
84	4.1711	2.61	.002
87	9.0922	2.18	.004
88	3.5077	3.63	.220
90	5.9736	2.69	.028
92	9.4593	1.95	.000
97	4.1616	2.71	.003
98	8.1103	1.80	.000
99	1.9239	3.41	.140
100	4.3800	3.29	.100
101	5.1608	2.92	.020

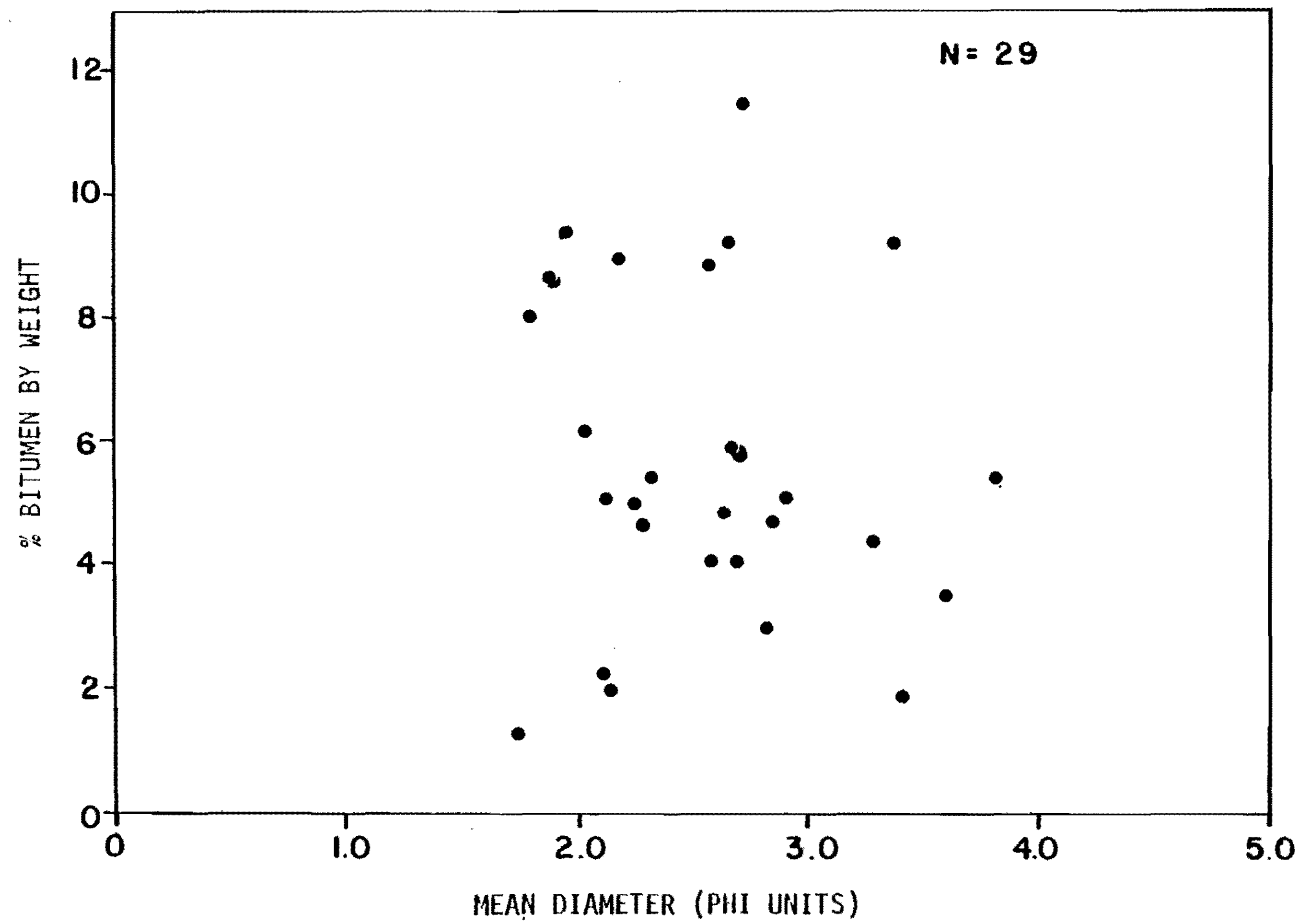


FIG. 26.--Scatter diagram of bitumen content versus mean diameter. Correlation coefficient = .09.

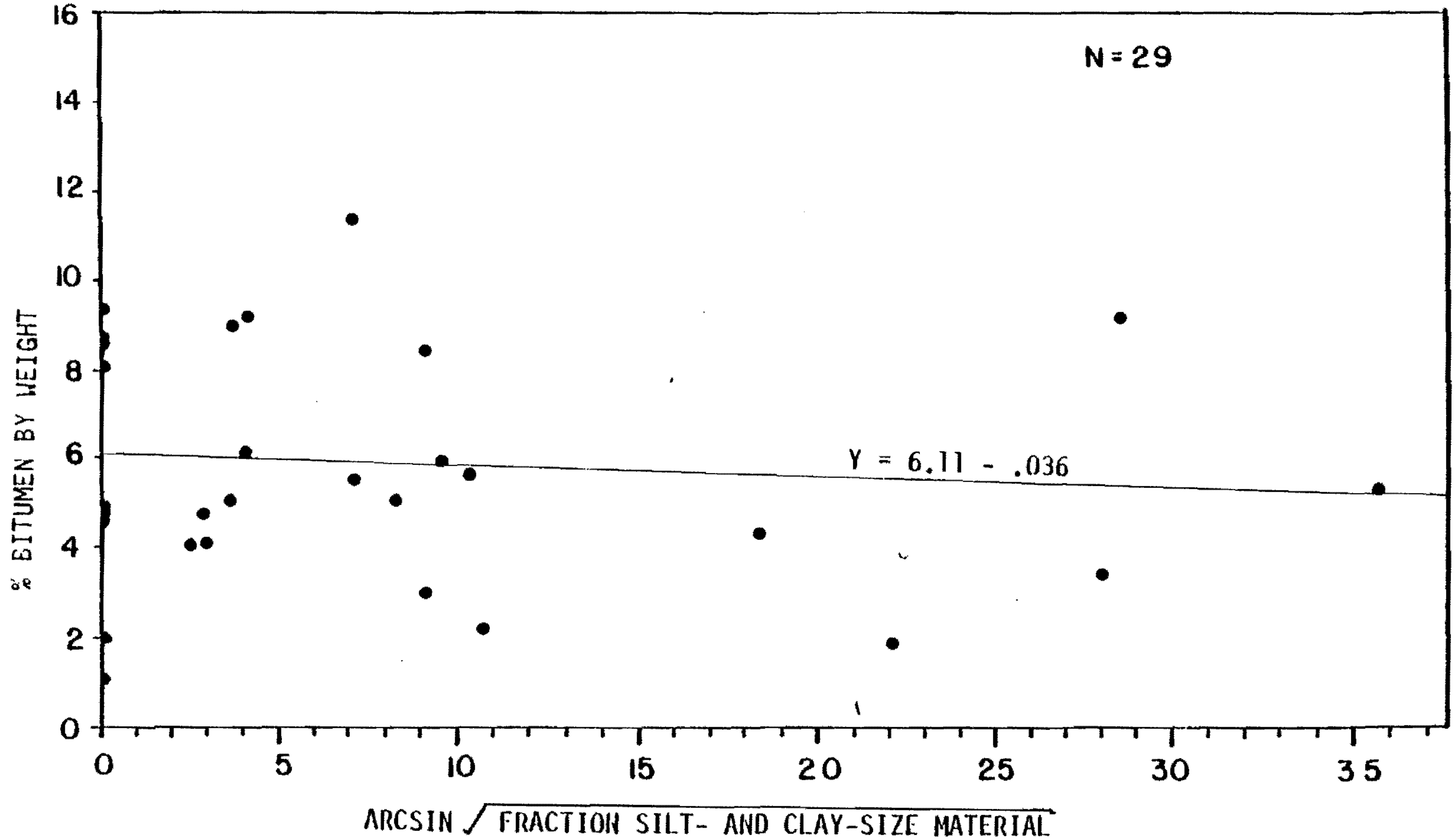


FIG. 27.--Scatter diagram of bitumen content versus arcsin √ silt- and clay-size fraction. Correlation coefficient = .14.

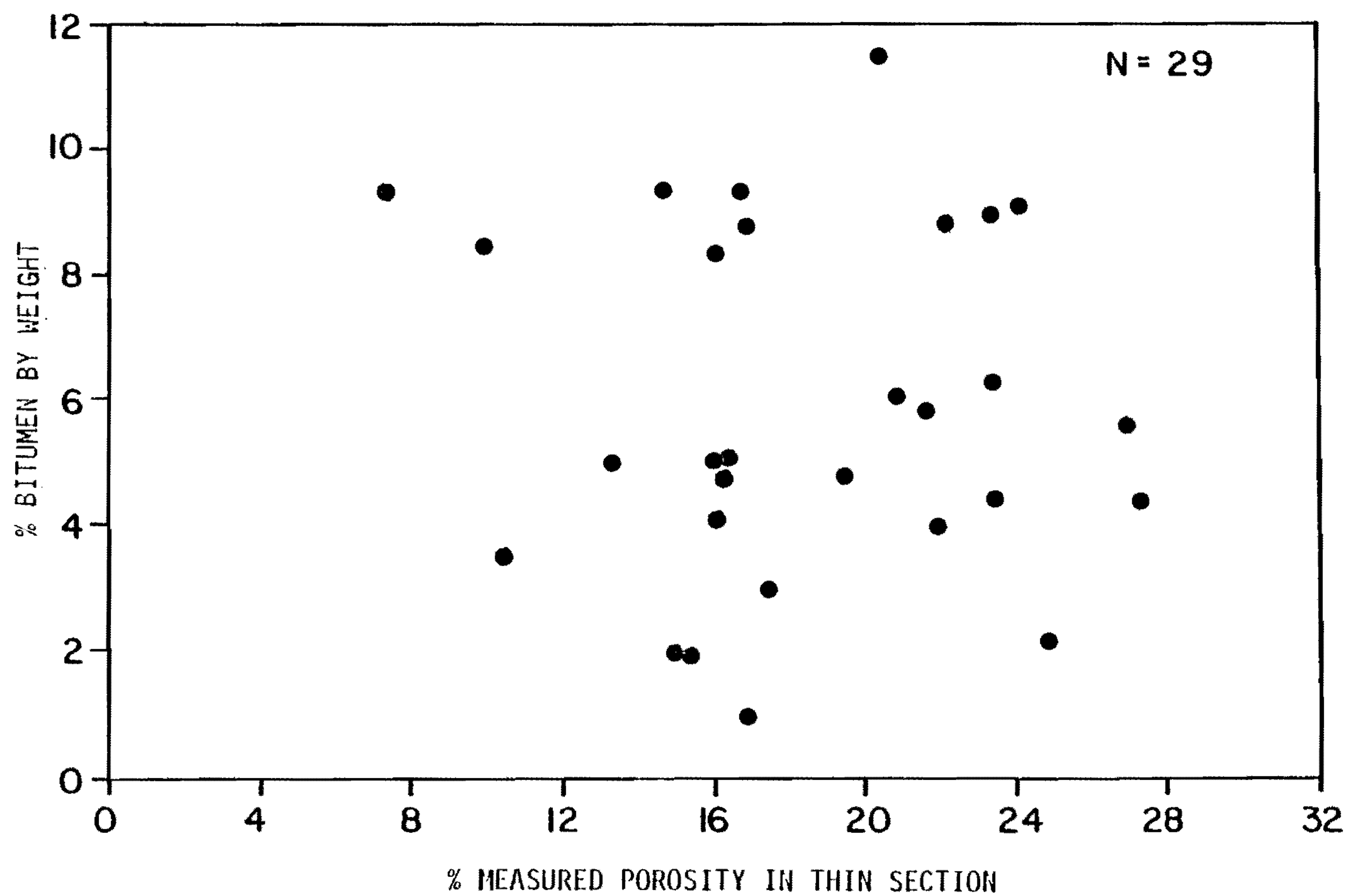


FIG. 28.--Scatter diagram of bitumen content versus measured porosity in thin section.

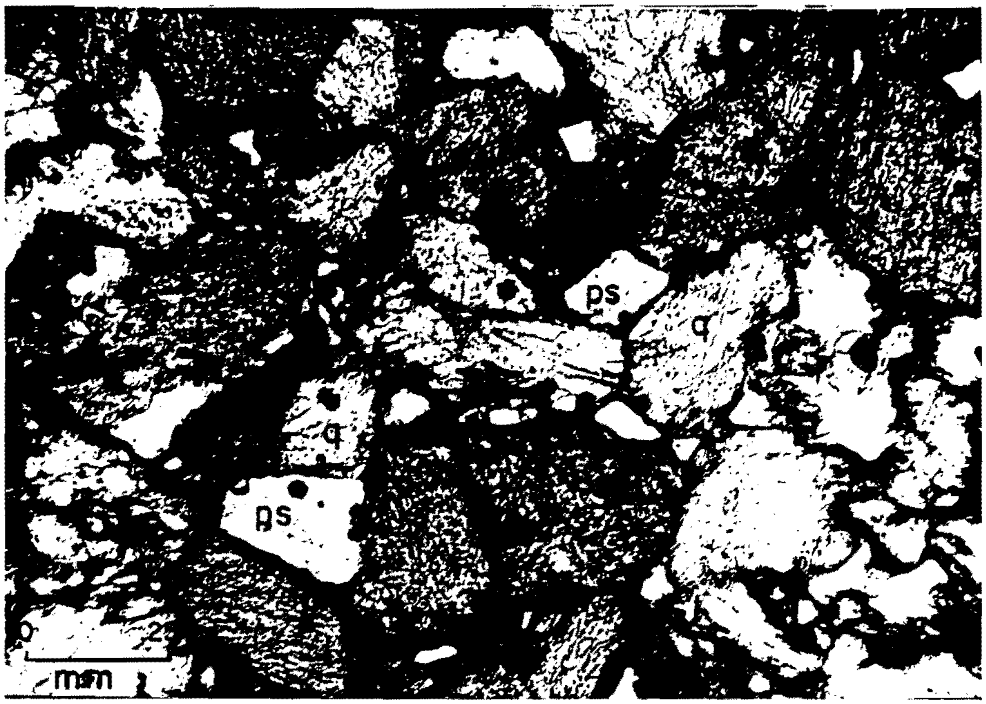


FIG. 29.--Partially saturated sandstone. Bitumen coats grains, but does not fill pore spaces. ps - pore space; k - k-fledspar; p - plagioclase; q - quartz. Plane polarized light.

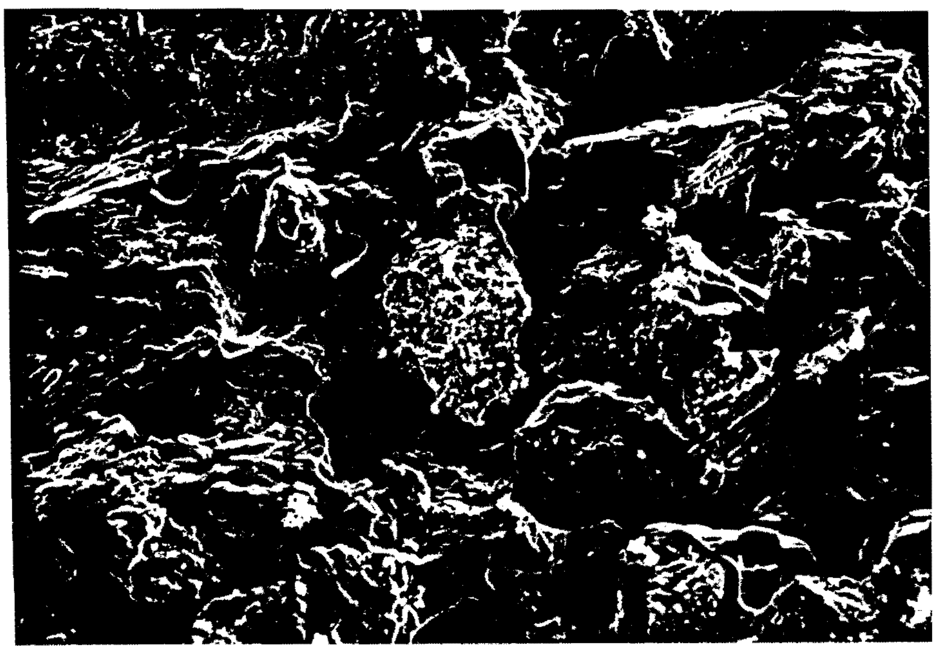


FIG. 30.--Oil-impregnated sandstone in which bitumen occurs as an amorphous coating on detrital grains. Bitumen does not completely fill pore spaces. SEM - 70x.

DIAGENESIS

Several diagenetic sequences are evident in the barren and oil-impregnated sandstone at Sunnyside. There are many similarities in the initial post-depositional diagenetic transformations of the two sandstone groups. The latter stages of diagenesis vary considerably, however, between the barren and oil-impregnated sandstone. The paragenesis of the two groups is summarized in Table 6.

Authigenic spar-size dolomite rhombs are disseminated throughout the barren and oil-impregnated sandstone. The random occurrence of the dolomite suggests it is a replacement product of a detrital grain, possibly a carbonate rock fragment or fossil fragment.

The development of syntaxial overgrowths of albite and quartz is also a common diagenetic event. Overgrowths are common in all sandstone except barren sandstone which contains a high percent primary matrix. The lack of other authigenic cements between individual grains and grain overgrowths and also between interlocking grain overgrowths indicates that the development of syntaxial overgrowths was an early event in the paragenesis of the sandstone, as was the development of the spar-size dolomite rhombs. Chemical conditions for authigenic feldspar growth must be such that a supply of dissolved silica and high Na^+/H^+ or K^+/Na^+ activities, as might be found in formation waters of high salt concentration, are present (Pettijohn and others, 1973, p. 429). The lacustrine environment of Eocene Lake Uinta went through cycles of evaporite deposition (Bradley, 1931;

Table 6.--Diagenetic Sequences of the Barren and Oil-Impregnated Clastic Rocks at Sunnyside

BARREN

I.
1. Minor compaction
2. Development of spar-size dolomite rhombs
3. Authigenic hematite

II.
1. Minor compaction
2. Development of spar-size dolomite rhombs and albite and quartz overgrowths
3. Authigenic hematite

III.
1. Minor compaction
2. Development of spar-size dolomite rhombs and albite and quartz overgrowths
3. Authigenic hematite
4. Mosaic pore-filling calcite cement

OIL-IMPREGNATED

I.
1. Minor compaction
2. Development of spar-size dolomite rhombs and albite and quartz overgrowths
3. Authigenic hematite
4. Migration of bitumen and etching of plagioclase
5. Development of microcrystalline dolomite

II.
1. Minor compaction
2. Development of spar-size dolomite rhombs and albite and quartz overgrowths
3. Authigenic hematite
4. Development of patchey pore-filling calcite cement
5. Migration of bitumen and etching of plagioclase
6. Development of microcrystalline dolomite and rare development of overgrowths on spar-size dolomite rhombs

Eugster and Surdam, 1973). Saline connate water or brine, high in Na^+, expelled during initial phase of compaction (Tissot and Welte, 1978, p. 285) may have migrated laterally into the marginal lacustrine and alluvial facies, producing the necessary chemical conditions for precipitation of authigenic albite and quartz. The low primary porosity of barren sandstone containing a high percent matrix material prevented the migration of formation waters through the sandstone, thus inhibiting the development of authigenic feldspar overgrowths. No evidence of the development of authigenic K-feldspar overgrowths was noted by either petrographic or microprobe analysis.

Irregularly distributed hematite commonly forms a thin coating on detrital grains and overgrowths. Hematite is preferentially concentrated around opaque mineral grains and radiates outward from time, though not all opaque grains exhibit this association. Spar-size dolomite rhombs are almost without exception associated with authigenic hematite. The hematite occurs in all stages of replacement of the dolomite rhombs, from a minor coating to complete replacement of the rhomb, leaving only a lattice work of microcrystalline hematite in rhombic shape (Fig. 31). Fossil fragments, in particular ostracode carapaces, are preferentially replaced by hematite and, often appear opaque in thin section because of the complete replacement.

Calcite cement is preferentially developed in barren sandstone as sparry mosaic pore-filling cement which is occassionally poikilotopic. Poikilotopic development of sparry calcite cement is not well understood. Sandstone with poikilotopic cement commonly exhibits loose packing of the detrital framework grains. Jonas and McBride (1977,

FIG. 31.--Microcrystalline hematite replacing dolomite rhomb. Plane polarized light.

p. 73) suggest this is an indication of cementation at very shallow depths by recrystallization or direct precipitation from a dilute solution (Dapples, 1979). Oil-impregnated sandstone occassionally exhibits patchey development of sparry calcite cement. Development of calcite cement is a latter stage in the diagenetic sequence and it is unlikely that calcite, as well as authigenic dolomite rhombs and albite and quartz overgrowths, could have developed before burial of a few tens of feet.

Bitumen migrated into the sandstone at Sunnyside after the development of spar-size dolomite rhombs, albite and quartz overgrowths and authigenic hematite. The relationship between the development of calcite cement and introduction of bitumen is unclear. It is possible that the development of calcite cement is related to the migration of bitumen and associated fluids into the sandstone at Sunnyside. The presence of oil has been found to be an inhibiting factor in the degree of diagenesis and that calcite cement is preferentially developed outside oil-bearing zones in water-bearing rocks (Yurkova, 1970). The presence of pore-filling calcite cement in barren sandstone and occassional patchey development of calcite cement in oil-impregnated rocks may be due to the segregation of oil and associated water within the sandstone.

Secondary porosity has been developed in oil-impregnated sandstone by the etching of plagioclase. The pore spaces of the etched plagioclase are saturated with bitumen. Because of the assocation of etched plagioclase with oil-impregnated sandstone it appears that etching of plagioclase is a result of chemical conditions present during the migration of bitumen into the sandstone.

Authigenic dolomite cement developed in oil-impregnated sandstone after migration of bitumen into the sandstone. The dolomite is present as isolated microcrystalline rhombs disseminated throughout the bitumen-filled pore spaces. Figure 32 shows an authigenic dolomite crystal developed on a bitumen-coated detrital grain.

Picard (1971, p. 20) believes bitumen in the P. R. Spring area, east of Sunnyside, originated in the lacustrine facies of the Green River Formation and migrated updip into the sandstone reservoirs. A similar explanation for the source of the bitumen in the Sunnyside deposit is suggested. Volatile fractions of the hydrocarbons evaporated on exposure to the surface, producing the concentration of "tar".

FIG. 32.--Authigenic dolomite crystal developed on bitumen-coated detrital grain. SEM - 550x.

PALEOCURRENT ANALYSIS

Methods

Eighty-eight orientation measurements were taken from sandstone cross-stratification exposures at Sunnyside. The average dip of the exposures, particularly in the northern part of the deposit, are minor, therefore no correction for tectonic tilt was necessary.

The Tukey (1954) Chi-square test for grouped orientation data was used to determine a central tendency of the orientation measurements. The theory and proofs of the Tukey Chi-square test have been presented by Durand and Greenwood (1958, appendix 2, p. 236-237) and Middleton (1965, p. 547-549, and 1967, p. 640). The vector resultant was determined by the vector summation method of Curray (1956, p. 118-119) using a calculator program developed by Lindholm (1979, p. 618). Magnitude of the vector resultant, which provides a measure of dispersion of data about the vector resultant, was also determined. Ninety-five percent confidence limits (θ) were calculated following the method of Steinmentz (1962, p. 806). Compass diagrams of paleocurrent measurements (see Fig. 2) show the 30° intervals which contain an observed number of measurements greater than one standard deviation from the average, as significant modes (High and Picard, 1971, p. 37).

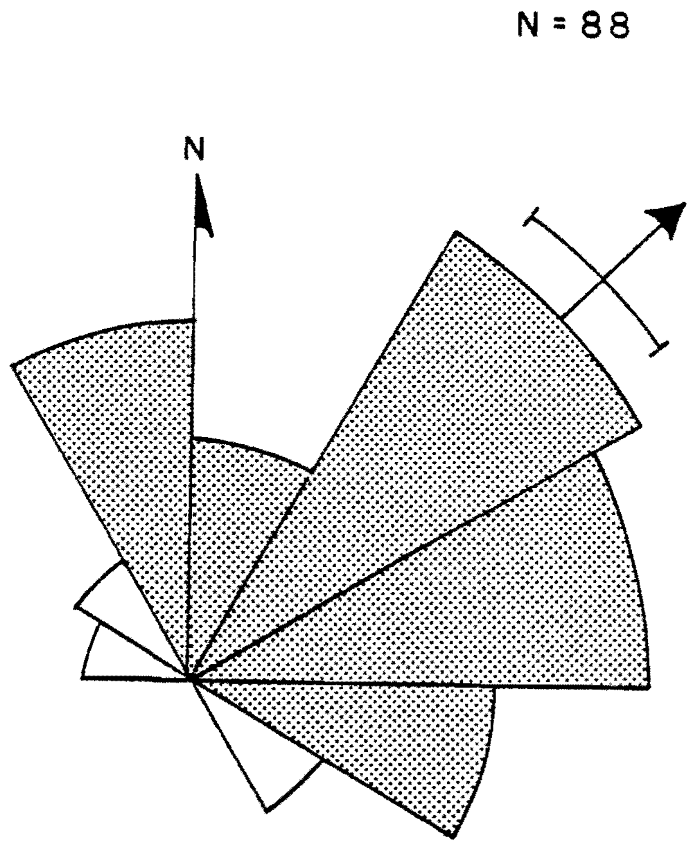
Results

Directional sedimentary structures observed in the sandstone at Sunnyside are small to medium scale planar and trough cross-stratification and ripple marks. The varieties of medium scale cross-stratification are the most abundant. Ripple marks are scarce. The majority of orientation measurements were obtained from medium scale planar cross-stratification with the remainder determined from trough orientations of medium scale trough cross-stratification. No measurements from ripple marks were obtained.

Siltstone and claystone, which overlies the oil-impregnated sandstone beds, is commonly eroded back from above the sandstone, providing excellent three-dimensional exposures of the upper part of the sandstone sequence. Planar cross-stratification is the most common structure in the upper part of the exposed sandstone and provides the most reliable exposures from which directional measurements can be made. Planar cross-stratification shows greater dispersion and less reliable paleocurrent results than does trough axis measurement (High and Picard, 1974). Meckel (1967), believes however, that planar cross-stratification measurements and trough axis measurements are comparable in measures of scatter and standard deviation.

Interpretation

A unimodal direction of transport to the northeast is indicated by the paleocurrent analysis (Fig. 33). A consistent sediment transport direction upward through the unit is shown by the compass diagrams in Figure 2. Comparison of the average direction of transport, N 45°E, with an isopachous map of the black shale facies of the Green River Formation (Picard and others, 1973, p. 14), a time equivalent lacustrine facies, shows a perpendicular relationship between the vector mean and isopach lines. The average shoreline of Lake Uinta in the



VECTOR RESULTANT	45.4°
MAGNITUDE OF VECTOR RESULTANT	61.4%
95% CONFIDENCE LIMITS	± 9.9°

FIG. 33.--Rose diagram of paleocurrent measurements from sandstone of the Sunnyside oil-impregnated sandstone deposit. Vector resultant direction and 95% confidence limits are shown. Stippled modes contain an observed number of measurements greater than one standard deviation from the mean.

Sunnyside area, during the deposition of the fluvial sandstone, was oriented northwest-southeast.

DEPOSITIONAL ENVIRONMENTS

The oil-impregnated section at Sunnyside consists of thick fluvial sandstone and subordinate flood plain deposits gradationally overlain by sandstone, siltstone, shale and carbonate of lacustrine origin. Intertonguing of the fluvial and lacustrine rocks is common, and the lower two-thirds of the oil-impregnated section is dominately fluvial and the upper one-third is dominately lacustrine.

Sedimentary Structures

Fluvial channel form sandstone contains the greatest variety of stratification types and sedimentary structures. Medium-scale trough cross-stratification is the most abundant structure (Fig. 34) and small-scale trough cross-stratification less common. Planar cross-stratification and horizontal stratification are also common (Figs. 35 and 36). Massive bedding of sandstone is present. Rare sedimentary structures are ripple marks, ripple stratification, parting lineation, and disturbed bedding.

The fine-grained flood plain rocks exhibit fewer sedimentary structures than the fluvial sandstones. The principal structures are horizontal lamination, burrowed structures, disturbed bedding, polygonal shrinkage cracks (Fig. 37).

Red and green claystone are present within the flood plain sequence of rocks, but the red clastics are the most abundant. The red claystone is more commonly stratified than the green claystone. Red

FIG. 34.--Medium scale trough cross-stratification. Bitumen leached out of the sandstone highlights the cross-stratification.

FIG. 35.--Medium scale planar cross-stratification.

FIG. 36.--Horizontal stratification.

claystone is often mottled in appearance and bedding is often indistinct and commonly weathers to a massive, conchoidal appearance in outcrop. Wood fragments and disseminated pyrite were observed only in the green claystone.

A variety of lacustrine rocks are present at Sunnyside. Lacustrine sandstone is distinguished by the abundance of medium-scale planar cross-stratification and lack of trough cross-stratification. Dolomitic lacustrine mudstone is thinly-bedded to massive. Lacustrine carbonate rocks vary from silty limestone and dolostone to algal beds and ostracode coquina. The majority of lacustrine carbonate rocks contain abundant allochemical constituents, in particular fossil fragments, oolites, and rarely intraclasts.

A summary of the characteristics of fluvial and lacustrine sandstone is presented in Table 7.

Fluvial Deposits

An upward fining trend in grain size, vertical variation of sedimentary structures from high to low flow regime structures, and interbedded red and green siltstone and claystone (Fig. 38) indicate that the laterally discontinuous, composite channel form sandstones are similar to vertical sequence to point bar deposits (Bernard and Major, 1963; Visher, 1965; Allen, 1970; Blatt and others, 1980). The channel form sandstones are up to 350 feet thick and several thousand feet in width. The fluvial sequence can be divided into two dominant units, the laterally accreting channel sandstone and the finer-grained vertical accretion flood plain deposits. Thickness of the two members

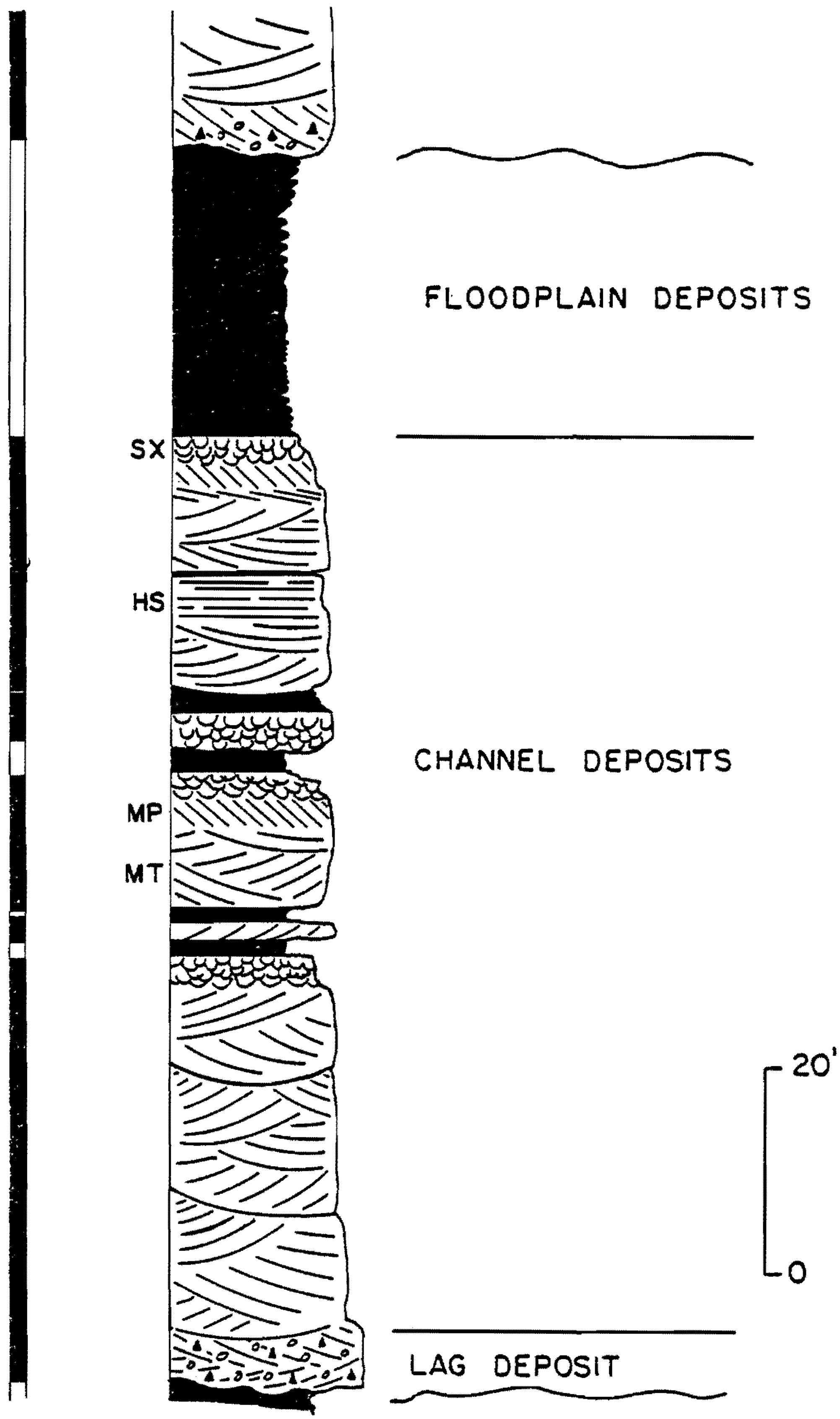
Table 7.--Summary of Characteristics of Fluvial and Lacustrine Sandstone, Sunnyside Oil-Impregnated Sandstone Deposit

Characteristics	Fluvial Sandstone	Lacustrine Sandstone
Bedding Types		
Cross-stratification		
Trough	a	r
Planar	c	a
Horizontal stratification	c	c
Disturbed bedding	r	r
Ripple stratification	r	r-c
Massive stratification	r	
Channel	c	
Sedimentary Structures		
Ripple Marks	r	c
Parting lineation	c	c
Sole marks	r	
Polygonal shrinkage cracks	r	r
Burrowed structures	r	r
Lithologies		
Conglomerate	c	
Green, silty mudstone	c*	
Red, silty mudstone	c*	
Allochemical constituents	r	a
Algal beds		c
Carbonate beds		a
Oil shale		c
Carbonate cement	r-c	c
Matrix	c	r-c
Petrified wood	r-c	
Vertebrate fossils	r	r

(r - trace to rare; c - common; a - abundant; blank space - not present or not observed)

* - occurs beneath fluvial channel sandstone and in associated flood plain deposits.

FIG. 38.--Stratigraphic section of a fluvial point bar upward fining sequence at Sunnyside. SX - small scale cross-stratification; HS - horizontal stratification; MP - medium scale planar cross-stratification; MT - medium scale trough cross-stratification. Blackened interval on left hand column indicates the oil-impregnated interval of the depositional sequence.


SX
HS
MP
MT
FLOODPLAIN DEPOSITS
CHANNEL DEPOSITS
LAG DEPOSIT
20'
0

varies vertically and laterally. The channel sandstone is generally thicker than the overlying flood plain deposits.

The channel sandstone exhibits a characteristic scoured surface which is overlain by a thin and often discontinuous channel lag deposit of medium to coarse-grained sandstone which contains small pebbles and intraformational mud clasts. Medium-scale trough cross-stratification, the most common stratification form, diminishes in set height upward through a channel sequence. Planar cross-stratification is restricted to the upper part of the point bar sequence and overlain by small-scale trough cross-stratification. Horizontal stratification occurs near the upper part of the sequence, but occassionally is present near the base of a sequence, overlain by trough cross-bed sets.

The thick point bar deposits are composed of a composite set of channels. Each channel exhibits the characteristic structures of point bar deposits but are truncated before the sequence is fully developed. Thin beds of laterally discontinuous siltstone to claystone are interbedded within the sandstone. Polygonal shrinkage crakcs are common in the thin fine-grained interbeds (Fig. 37), providing evidence of intermittant aerial exposure of portions of the point bar.

Red and green siltstone and claystone of the associated flood plain facies overlie the channel sandstone. Ryder and others (1976, p. 508) attribute the red coloration of the majority of the flood plain deposits to a well-drained, oxidized environment. Green claystone commonly occurs beneath a channel sandstone (Fig. 39). The reduction of ferric iron by water percolating downward from the overlying channel is responsible for the green coloration (Ryder and others, 1976). Channel sandstone cross-cuts the finer-grained flood plain deposits, laterally truncating the siltstone and claystone beds (Fig. 39). The cohesive nature of the bank material is considered an important factor influencing meander development in a fluvial system (Schuum, 1960).

Channel-fill deposits associated with the thicker point bar deposits provide evidence of channel abandonment. Blatt and others (1980) cite three processes by which channel-fill deposits are developed: 1) meander cutoffs, 2) avulsion, and 3) gradual discharge reduction. Figure 40 shows a channel-fill deposit within a thick point bar deposit. It is finer-grained than the channel sandstone and exhibits concave bedding which conforms to the channel shape. These characteristics are common to a channel fill deposit in a meandering system (Schuum, 1968). Reinick and Singh (1980) suggest that the smaller channel-fill deposits of a meander system are produced by chute cut-offs, in which the bedload gradually diminishes. They are composed of finer-grained material than the point bar sandstone.

Meandering systems are favored by broad low relief basin floors which allow for migration and avulsion of meander belts. Preservation potential of the finer-grained flood plain deposits is poorly understood and the lack of subordinate amounts of vertical accretion deposits is not evidence against a meander system (Jackson, 1978). Migration and switching of a meander belt often erodes the flood

FIG. 40.--Channel-fill deposit (cf) interbedded within composite point bar sandstone. Thickness of channel-fill deposit approximately 15 feet.

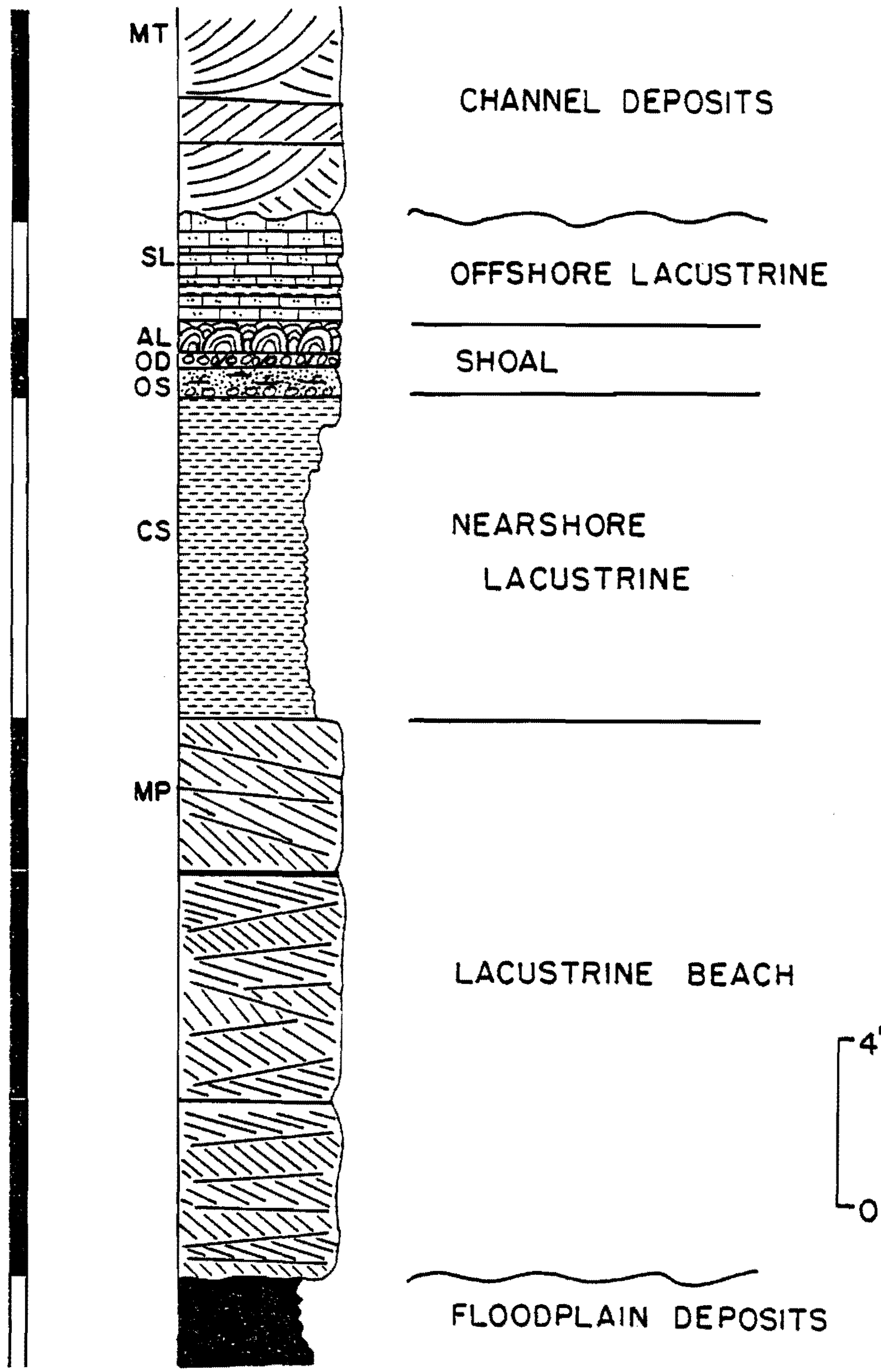
plain deposits and leads to the development of a blanket sand equal to the width of a valley floor (Visher, 1965; Jackson, 1978).

The fluvial oil-impregnated sandstone at Sunnyside outcrop for a distance of nine miles near the crest of the Roan Clifs. The composite channel form sandstone was deposited up slope from the deltaic environment on the southern margin of Lake Uinta (Ryder and others, 1976). Branching of the main drainages and periodic avulsion of the individual meander belts along with lateral channel migration within the meander belts produced a sand-dominated sequence. Thick sequences of flood plain deposits may have been developed adjacent to the aggrading meander belts and have been eroded when avulsion of the belts occurred.

Lacustrine Deposits

Sandstone of the lacustrine facies represents lacustrine littoral deposition. Medium-scale planar wedge cross-stratification (Fig. 41) is the dominant structure (Reinick and Singh, 1980, p. 107). Foresets of the planar cross-strata have a distinct southern component to the paleocurrent directions in contrast to the fluvial paleocurrent directions. Picard and High (1970), in a study of the fluvial and lacustrine sandstone at P. R. Spring area, Utah, identified a similar bimodal pattern between fluvial and lacustrine paleocurrent directions. Onshore current directions in the lacustrine sandstone is the dominant mode preserved at P. R. Spring and is opposed 180° to the fluvial paleocurrent directions. Poor outcrop exposures of the lacustrine sandstone at Sunnyside prevent precise determination of the paleocurrent directions.

FIG. 41.--Stratigraphic section of a prograding lacustrine depositional sequence. MT - medium scale trough cross-stratification; SL - silty limestone; OD - oolitic dolomite; OS - oolitic sandstone; CS - thinly-laminated carbonate rich siltstone and claystone; MP - medium scale planar cross-stratification. Blackened interval on left hand column indicates an oil-impregnated interval in the depositional sequence.


MT
SL
AL
OD
OS
CS
MP
CHANNEL DEPOSITS
OFFSHORE LACUSTRINE
SHOAL
NEARSHORE LACUSTRINE
LACUSTRINE BEACH
FLOODPLAIN DEPOSITS
4'
0

The lacustrine sandstone geometry at Sunnyside is different from the fluvial sandstone geometry. Lag conglomerate and basal scour surfaces are absent. The sandstone is tabular with a flat upper and lower bounding surface and has a greater lateral extent than the fluvial sandstone.

Nearshore lacustrine deposition of very fine-grained clastics is represented by thinly-laminated carbonate rich siltstone and claystone, which overlie the lacustrine sandstone.

Thin algal beds, oodolomicrite and biodolomicrite indicate offshore shoal development. Oolites were formed by constant agitation in shallow carbonate-rich waters. Algal reefs were developed in shallow, clear water (Bradley, 1929a, p. 222). Oolites and clastic grains wedged between lobate colonies of algae imply that either the environment favoring development of oolites and algae were closely related or strong currents occassionally swept allochems and detrital grains offshore across the algal reef.

Continued transgression developed carbonates of an offshore lacustrine facies. A minor amount of silt was carried offshore and deposited. The silty partings may represent sudden influxes of clastic material due to agitation by storms or periodic flooding.

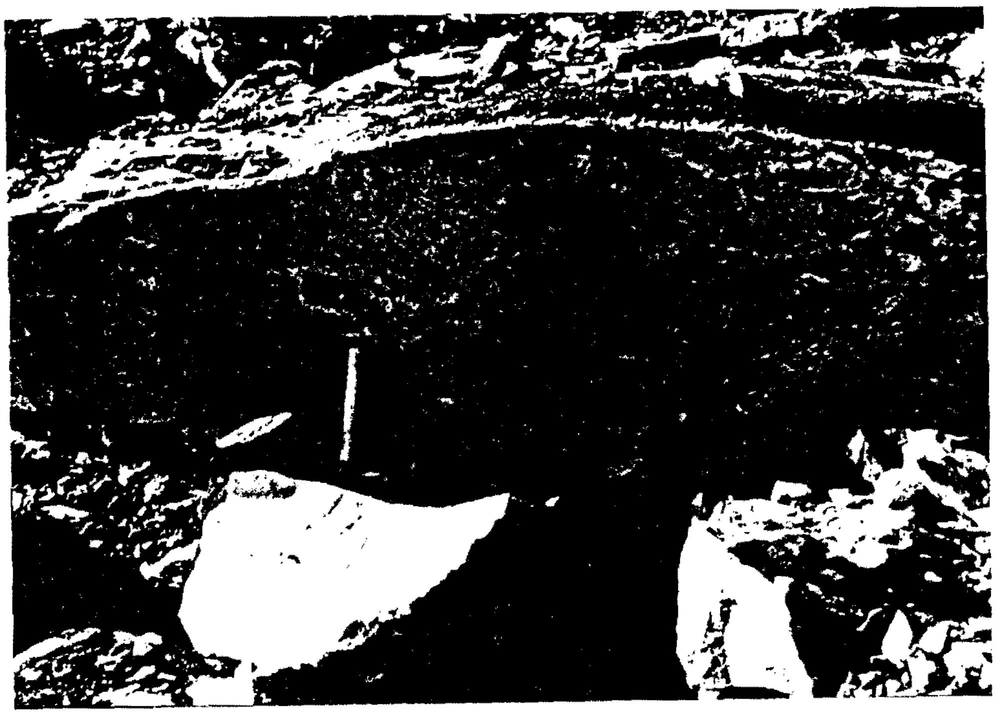


FIG. 37.--Polygonal shrinkage cracks.

PROVENANCE

The oil-impregnated sandstone and siltstone at Sunnyside are dominately arkose. Folk (1974) describes the genetic significance of three types of arkose: climatic, volcanic and tectonic. The climatic arkose is indicative of a dry climate which prevents rapid decomposition of the feldspar in the crystalline source area. This type of arkose is represented by mature to supermature sediments composed of rounded, fresh feldspar. Feldspar derived by rapid erosion of volcanic terrane and associated with volcanic biotite and quartz is characteristic of a volcanic arkose. Rapid tectonic uplift produces a tectonic arkose, characterized by the mix of fresh and badly weathered feldspar which is associated with igneous and metamorphic rock fragments, metamorphic heavy minerals and sedimentary rock fragments.

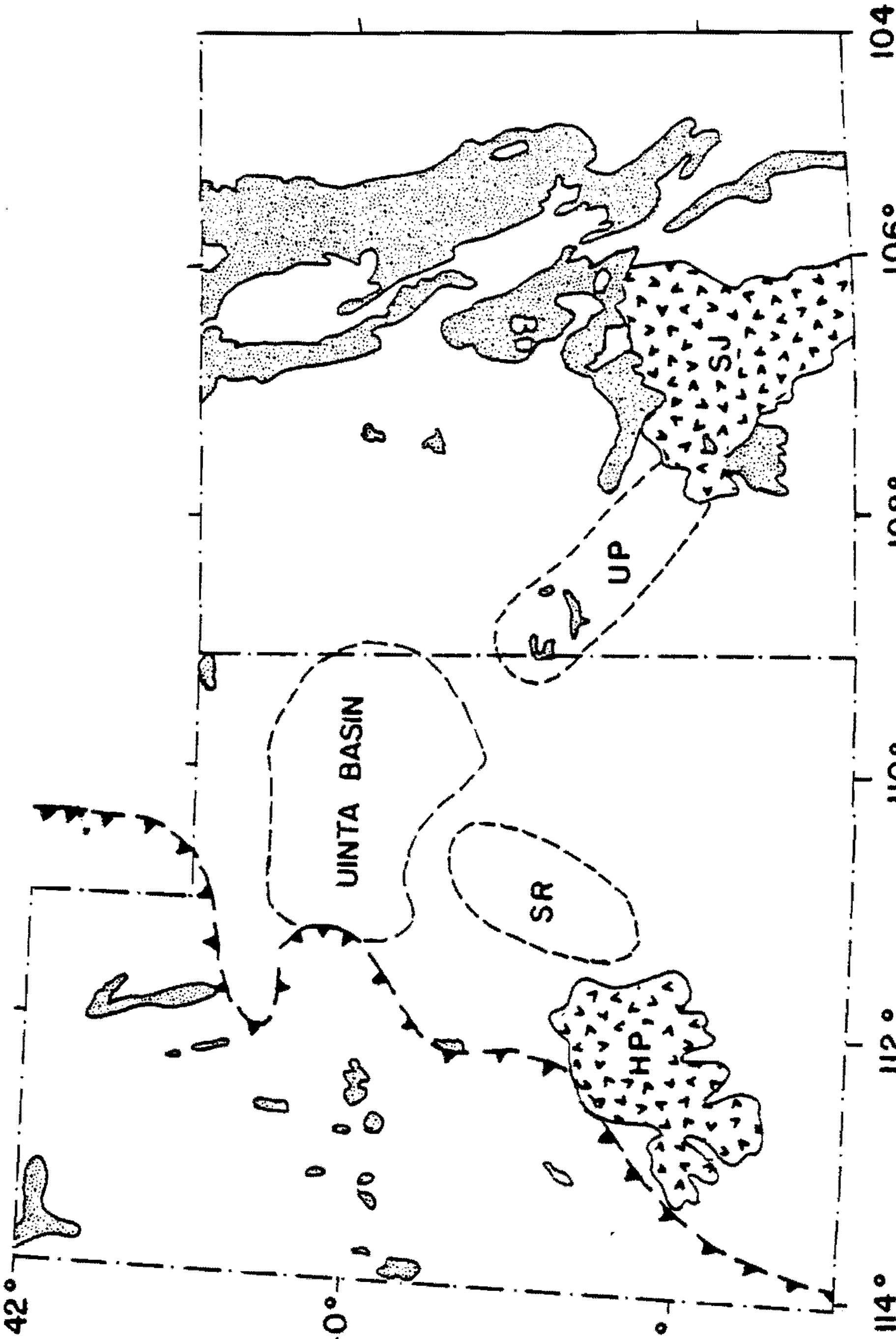
A mixed provenance for the fluvial rocks at Sunnyside has been established from petrographic evidence. Crystalline terrane provided the majority of detrital material with a minor contribution from sedimentary rocks. Laramide warping of the sedimentary blanket of Mesozoic carbonates and clastics on the Colorado Plateau, in particular, the San Rafael Swell to the south and southwest and the Uncompahgre Plateau to the southeast of the Sunnyside area, formed highlands of sedimentary rocks which were the source of much of the sedimentary detritus. Mesozoic rocks in particular Cretaceous carbonates, are probably the source of most of the detrital chert grains.

A sample from the very base of the oil-impregnated section (SS-70) contains an anamolously high percentage of chert relative to other samples located higher in the section. Reworking of Cretaceous carbonate provided the chert; however, as Tziassic and Jurassic rocks were exposed and eroded, the amount of detrital chert decreased, and clastic sedimentary rock fragments and reworked detrital grains became dominant. An inverted stratigraphic layering of sedimentary rock fragments is reflected in this relationship.

Present day exposures of Precambrian rocks in Colorado and Utah (Fig. 42) have changed little since Eocene time with two notable exceptions. Precambrian outcrops in the San Juan region of southwestern Colorado, present during deposition of the rocks at Sunnyside, were covered by volcanic rocks during middle to late Eocene time. Basin and Range extensional faulting during late Tertiary time obscured large parts of the Sevier orogenic belt and possibly exposures of Precambrian basement associated with the orogenic belt.

The style of deformation of the Sevier orogenic belt, folding and eastward thrusting of the Cordilleran geosynclinal sequence and Precambrian rocks, did not expose large areas of Precambrian basement as did the Laramide regional basement uplift of the Rocky Mountains. Sandstone derived from the Sevier orogenic highlands during the Cretaceous (Armstrong, 1968) and Lower Tertiary periods (Vine and Tourtelot, 1970, p. 256) is second-cycle, eroded from the thick Paleozoic and Mesozoic geosynclinal sequence, and is commonly quartz-rich (Vine and Tourtelot, 1970, p. 256). The appearance of arkosic detritus in the Rocky Mountain intermontane basins did not occur

FIG. 42.--Important geological features in Utah and Colorado. Structural features are outlined by dashes, SR - San Rafael Swell and UP - Uncompahgre Plateau. Volcanic terranes are shown in v-pattern, HP - High Plateaus volcanic field (Oligocene, Miocene, and Pliocene) and SJ - San Juan volcanic field (Middle Eocene). Present day outcrops (stippled) of Precambrian crystalline rocks located east of the Utah thrust belt and Precambrian crystalline and metasedimentary rocks located west of the Utah thrust belt in Colorado and Utah.


42°
40°
38°
114°
112°
110°
108°
106°
104°
UINTA BASIN
SR
UP
SJ
HP

until late Paleocene-early Eocene time (Vine and Tourtelot, 1970, p. 251), the time of maximum intensity of Rocky Mountain basement uplifts (Keefer and Love, 1963).

The average paleocurrent direction of N 45°E indicates a source area to the southwest, which is in agreement with the findings of Campbell and Ritzma (1979, p. 9). However, there were no extensive exposures of crystalline rocks to the west or southwest which could have provided the arkosic material. The only possible source for the arkosic material was from exposures of crystalline rocks in the Rocky Mountains in Colorado. The major pre-volcanic uplift of the San Juan Mountains in southwestern Colorado was probably the primary crystalline source terrane. Schistose and gneissic rocks make up the greater part of the Precambrian basement now exposed in the area (Larsen and Cross, 1956, p. 17), but granitic and metasedimentary rocks are also present (Edwards, 1966, p. 66). The anamalous eastern component of the average paleocurrent direction may be due to 1) the influence upon drainage pattern of the San Rafael Swell upwarp, and/or 2) the confluence of eastward and northeastward-flowing rivers, which drained the orogenic highlands to the west, with the northerly-flowing drainage at the northern end of the San Rafael Swell.

CONCLUSIONS

Sandstone of the Sunnyside oil-impregnated sandstone deposit was deposited in a meandering-stream environment on the southern margin of Eocene Lake Uinta. Fluctuations of the lacustrine environment are recorded by the presence of prograding lacustrine sequences of the Green River Formation interstratified with fluvial sandstone and flood plain deposits.

The sandstone at Sunnyside is dominantly arkose. Microprobe analysis of detrital feldspar, the rock fragment population and the heavy mineral assemblage of the sandstone indicate the arkosic detritus was derived primarily from a plutonic and metamorphic terrane with a subordinate contribution from sedimentary rocks.

The average paleocurrent direction of the sandstone is N 45°E, which indicates a source to the southwest. However, no terrane existed to the southwest or west which could have provided the arkosic detritus. The crystalline source terrane was probably in southwestern Colorado. Rivers draining the source area flowed northwestward and northward in a broad valley between the San Rafael Swell and Uncompahgre Plateau. The depositional site was several hundred miles from the source area, therefore the drainage pattern was no longer affected by the regional slope of the mountainous uplift. The topographic presence of the San Rafael Swell and the confluence of the major drainage at the northern end of the San Rafael Swell with streams draining the western highlands probably locally influence the drainage pattern in the area.

Diagenetic events include development of spar-size dolomite rhombs, syntaxial overgrowths of albite and quartz, hematite, calcite pore-filling cement and microcrystalline dolomite. In situ alteration of Fe-bearing minerals, in particular the Fe-silicate minerals biotite and hornblende, was the source of the authigenic hematite. Sparry mosaic pore-filling calcite cement, common in barren sandstone, occurs as random patchey cement in oil-impregnated sandstone. The development of calcite cement may be related to the migration of bitumen and associated pore fluids into the sandstone. No apparent relationship exists between percent bitumen by weight, and mean grain size and percent matrix due to incomplete saturation of the rocks by bitumen.

APPENDIX A

REFLUXION PROCEDURE

1. A double thickness thimble; Cat. No. 27732-145 or Cat. No. 27732-087, obtained from VWR Scientific must be used.

2. Material having a fine sand size distribution should be extracted using a double thickness cellulose thimble, Cat. No. 27732-097. In the worst case only .05% of the sand has been observed to pass through the thimble.

3. Dry the thimble in an oven for 2 hours at 60°C. After drying, store in a vacuum desiccator and bring to room temperature.

4. Take about 20 grams of oil-impregnated sand material.

5. The exact weight of the thimble plus material must be taken using a balance having accuracy of one thousandth of a milligram or so.

6. Place the thimble plus material in the neck of the specially designed flask (Dean-Stark apparatus) containing 200cc of toluene and some boiling chips.

7. Reflux 8 hours. While refluxing, care must be taken not to overflow the sample containing thimble. This can be adjusted by control of the heating system.

8. Toluene vapors dissolve the bituminous material in the sample and also remove the water present in the sample. The water droplets are condensed and collected in the graduated capillary tube, while toluene is refluxed.

9. The volume of water can be determined directly from the graduated tube.

10. Remove the cellulose thimble and dry at 80°C in an oven for 8 hours. Bring to room temperature in a vacuum.

11. Weigh on the balance (as described above) the amount of solids left in the thimble and calculate the bitumen content by difference.

Precaution:

1) Soxhlet extraction technique <u>can not be used</u> -- only Dean-Stark.

2) Double-thickness cellulose must be used.

3) While refluxing care must be taken to observe the toluene is not overflowing the thimble.

4) High accuracy chemical balance having one thousandth of a milligram must be used.

APPENDIX B

RESULTS OF MICROPROBE ANALYSIS OF DETRITAL FELDSPAR

(Mole Percent)

Sample #	An	Or	Ab	Corrected Total
SS - 84	15.35	0.83	83.82	98.06
	0.40	18.92	80.68	97.23
	0.00	96.36	3.64	100.36
	1.46	0.55	97.99	99.45
	0.00	97.03	2.97	100.67
	0.43	2.31	97.27	98.54
	24.63	1.02	74.35	100.51
	0.00	89.80	10.20	100.32
	1.07	0.66	98.27	98.34
	0.00	91.67	8.33	101.09
	0.00	94.96	5.04	100.23
	1.08	0.75	98.17	98.19
	0.03	2.13	97.84	98.04
	0.87	7.89	91.24	97.41
	0.00	95.68	4.32	100.68
	6.40	4.84	88.76	99.57
	0.00	96.38	3.62	100.42
	1.53	2.14	96.33	99.01
	0.00	0.22	99.78	99.48
	0.00	0.40	99.60	99.62
	3.49	0.15	96.36	98.17
	0.00	0.00	100.00	99.70
	0.00	92.10	7.90	100.39
	2.50	1.95	95.55	99.06
	0.00	90.69	9.31	100.95
	0.61	1.20	98.19	98.78
	0.59	0.03	99.38	99.36
	15.24	0.39	84.38	99.74
SS - 87	1.85	0.65	97.50	99.97
	1.79	94.20	4.10	99.99
	14.67	0.91	84.42	99.70
	2.59	93.40	4.01	99.12
	1.32	0.58	98.09	98.40
	1.69	0.47	97.84	97.98
	3.09	68.49	28.42	97.30

APPENDIX B (cont.)

Sample #	An	Or	Ab	Corrected Total
	(Mole Percent)			
SS - 87	2.28	9.11	88.61	95.92
	19.32	0.60	80.62	98.35
	2.52	0.55	96.92	98.96
	1.48	0.17	98.35	98.33
	1.53	0.44	98.03	98.23
	2.08	1.74	96.17	98.44
	2.14	8.06	89.80	98.98
	1.53	90.30	8.17	100.35
	2.78	0.35	96.88	99.28
	2.11	0.46	97.44	99.08
	1.66	87.10	11.25	100.90
	2.83	0.57	96.60	99.35
	1.53	92.39	6.08	100.29
	2.42	0.89	96.69	99.84
	1.44	93.91	4.65	99.74
	1.77	1.13	97.10	98.02
	1.41	0.50	98.09	99.29
	3.74	4.22	92.03	98.75
	1.74	0.21	98.05	99.00
SS - 90	1.25	0.60	98.14	99.71
	2.05	0.78	97.17	99.74
	1.63	81.22	17.15	100.87
	1.76	3.11	95.13	98.06
	7.76	1.12	91.12	98.86
	1.50	92.07	6.43	101.34
	1.67	95.23	3.10	99.62
	25.21	0.55	74.23	100.21
	1.52	0.84	97.64	98.06
	25.21	1.01	73.78	100.35
	1.45	94.88	3.67	100.64
	1.63	92.72	5.65	101.37
	1.39	92.52	6.09	101.00
	2.61	0.79	96.60	98.40
	1.48	92.28	6.23	101.13
	1.70	0.45	97.85	98.78
	1.79	91.99	6.22	101.33
	2.14	0.94	96.92	96.52
	2.13	1.85	96.02	99.09
	1.96	0.91	97.13	98.49
	1.44	93.91	4.65	101.05
	1.04	0.15	98.81	99.54
	17.38	2.88	79.75	96.81
	1.04	94.00	4.69	100.67

APPENDIX B (cont.)

(Mole Percent)

Sample #	An	Or	Ab	Corrected Total
SS - 90	2.25	0.60	97.15	98.86
	1.80	78.07	20.13	100.82
	1.27	0.43	98.29	98.42
SS - 92	2.42	1.36	96.22	98.68
	1.47	63.61	34.92	100.93
	18.77	1.41	79.82	99.57
	1.03	92.36	6.60	100.75
	14.79	0.68	84.53	99.94
	10.15	1.11	88.74	99.80
	4.39	1.55	94.06	99.00
	0.95	95.19	3.86	101.43
	1.45	0.74	97.81	99.35
	20.85	2.12	77.03	99.09
	8.94	1.05	90.01	98.22
	20.14	1.81	78.05	100.40
	21.77	0.72	77.52	100.43
	1.33	94.22	4.45	100.79
	5.43	1.43	93.13	100.04
	2.66	0.86	96.48	98.68
	2.18	1.23	96.59	99.12
	1.66	93.12	5.22	101.49
	1.97	0.95	97.08	99.76
	2.12	88.98	8.90	101.01
	1.46	95.26	3.28	101.47
	13.05	1.12	85.83	99.37
	3.42	1.37	95.21	96.53
	21.23	2.55	76.22	100.70
SS - 54	0.00	93.91	6.09	101.40
	0.00	94.08	5.92	100.84
	0.60	0.34	99.05	98.87
	0.78	0.79	98.43	99.17
	0.74	95.46	3.80	101.25
	0.13	1.94	97.92	98.78
	0.37	1.30	98.33	99.16
	14.66	7.07	78.27	99.29
	21.86	1.16	76.98	99.34
	0.00	97.22	2.78	100.64
	14.44	1.22	84.35	99.98
	0.07	97.40	2.53	101.07
	0.57	91.15	8.27	100.86
	0.60	63.02	36.38	100.72
	0.49	94.49	5.02	101.31
	20.48	0.96	78.56	100.34

APPENDIX B (cont.)

Sample #	An	Or	Ab	Corrected Total
		(Mole Percent)		
SS - 54	0.97	0.69	98.35	99.66
	0.40	91.78	7.82	101.26
	1.91	1.72	96.37	99.71
	0.60	96.20	3.74	101.29
	1.26	0.31	98.43	99.25
	0.37	00.33	99.30	99.20
	3.16	1.73	95.11	97.16
	0.45	94.82	4.73	100.96
	0.83	1.12	98.05	99.49
	4.37	0.92	94.71	99.09
Overgrowths	0.02	0.35	99.63	99.33
	0.03	0.31	99.66	98.63
	0.43	0.30	99.27	99.24
	0.00	0.22	99.78	96.75
	1.87	0.81	97.32	99.30
	2.08	1.18	96.74	97.46
	2.26	0.52	97.22	99.02
	1.84	0.83	97.34	99.13
	1.87	0.79	97.34	98.21
	1.44	0.95	97.61	96.70
	1.87	0.00	98.13	97.70
	1.51	0.11	98.38	98.46
	1.81	0.44	97.75	97.78
	1.91	1.58	96.54	98.75
	2.23	0.77	97.00	96.65
	1.44	0.59	97.97	97.57
	1.70	0.24	98.06	97.02
	0.00	1.21	98.79	97.77

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